NUMERICAL MODELLING OF A LATERALLY LOADED PILE GROUP BY FINITE ELEMENT METHOD

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Abstract of Dissertation Presented to the Graduate School of the University of Florida in Partial Fulfillment of the Requirements for the degree of Doctor of Philosophy

NUMERICAL MODELLING OF A LATERALLY LOADED PILE GROUP BY FINITE ELEMENT METHOD

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The main purpose of this research is to create a nonlinear finite element computer program (LPG) specifically for analyzing a laterally loaded pile group. In the program, piles are modeled by 3-D finite beam elements. Pile-soil and pile-soil-pile interaction among the piles and soil within the group is modeled by soil springs. The interaction is assumed to be effected by two types of springs, near-field and far-field soil springs. The near field soil springs are nonlinear and their stiffnesses are obtained from p-y curves. The far-field soil springs are linear and their stiffnesses are obtained from Mindlin's flexibility equations. Axial loads are transferred to the soil through the axial linear soil springs attached to the tips of the piles. Input parameters for all the soil springs can be obtained from insitu and/or laboratory tests.

The program gives both linear and nonlinear solutions comparable to the solutions of a commercially available software (COM624) for a laterally loaded single pile. It also gives Poulos's Integral Solution for a laterally loaded linear elastic pile group system.

Finally, the program was used to predict both a single pile and pile group response at a Houston, Texas, site for static and cyclic loadings. Good results were obtained for both cases using the same soil parameters obtained from the site.

CHAPTER 1
INTRODUCTION

1.1 General

Pile groups are subjected to lateral loads under a variety of situations, such as seismic loads, wind loads, ship impacts, etc. Three options are available to design such groups:

1. A full scale load test
2. A centrifugal model test
3. A rational theory

Generally the first option is economically not viable and the second has the disadvantage of not exactly modelling the insitu soil behavior. So the third option is often resorted to. Previously, theories modelling soil as an elastic half space (17,18) were used for the design. But the current trend uses theories that account for nonlinear behavior of soils.

1.2 Objective

The primary objective of this research is to create a finite element computer program that would calculate a load deflection curve for a laterally loaded pile group. The program would model each pile in the group with linear

elastic beam elements, pile-soil interaction (lateral soil resistance) with nonlinear elastic springs and pile-soil-pile interaction with linear springs. The choice of spring models for the soil, to predict a single pile or group response, is selected such that input parameters may be obtained from insitu tests such as SPT and/or CPT and laboratory tests such as triaxial compression test.

A comparison with a closed form solution using an entirely linear system is used to assess the accuracy of the program. Finally, field load test data obtained for the pile group study at Houston, Texas (3) are used to evaluate the program and its representative soil and/or pile models. In this latter study, the soil material parameters used in the single pile predictions are also used in the group analysis.

1.3 Scope

The work carried out for this dissertation could be divided into four parts:

1. Incorporate nonlinear p-y curves/springs to depict pile-soil interaction and Mindlin linear springs to depict pile-soil-pile interaction;
2. Add linear finite element of the pile segments and solve iteratively by secant method;
3. Verify the algorithm in the case of a linear system with available integral solutions and program COM624 (23);

4. Model one of the few field studies with single and pile group response.

CHAPTER 2
LITERATURE REVIEW

In general there are four analytical models for pile group behavior:

1. Finite element model
2. Continuum model
3. Unit load-transfer model
4. Hybrid model

A three-dimensional finite element model could represent the nonhomogeneous and nonlinear nature of soils very well. But it has the disadvantage of not exactly knowing constitutive models, correct soil parameters, and the initial states of stress surrounding the piles. In addition, it is very expensive and time-consuming to run. For example, Brown (4) took 15 to 20 hours of CPU time on a Cray X/MP24 super-computer to analyze two rows of piles. Some other examples for laterally loaded pile group research using FEM include those of Kimura et al. (9), Selby and Arta (24) and Trochanis et al. (27).

A continuum model assumes the soil as a linear elastic half space and uses Mindlin's three-dimensional elasticity equations to model pile-soil and pile-soil-pile interaction. Examples of this model are Poulos (17,18) and Sharnouby and Novak (25). To reduce the computational effort, a modified

continuum model was proposed. The modified model (or coupled Winkler model) is similar to the continuum model except that the pile-soil-pile interactions are assumed to occur only in horizontal planes. Examples include those of Nogami and Chen (15) and Randolph (19).

A unit load-transfer model is described by Bogard and Matlock (2). In this model, nonlinear load-transfer/p-y curves for piles in a group are constructed empirically by combining a p-y curve for a single pile and a p-y curve for an imaginary pile with a large-diameter representing the piles within the group and the encompassed soil acting together.

A hybrid model was initially proposed by Focht and Koch (5). The Focht-Koch hybrid model is a combination of continuum and unit load-transfer models. It uses linear elastic interaction factors obtained from the continuum model proposed by Poulos (17,18). It indirectly considers the nonlinear pile-soil interaction, technically called p-y curve, in the equations of elasticity used in the continuum model, by introducing a relative stiffness factor. A similar but more refined procedure was proposed by O'Neill et al. (16). In O'Neill's model, instead of using the linear elastic interaction factors derived from the continuum model, the piles were discretized and FEM was used to calculate displacements. Displacements at the location of each p-y curve on each pile are computed from the load of all other pile elements using Mindlin's point load equations

(13) and each p-y curve was individually modified for the effect of other piles i.e. to account for pile-soil-pile interaction. The response of each pile is recomputed using the modified p-y curves and the process repeated. Like O'Neill's model, the model suggested recently by Brown (3) also corrects the p-y curves for isolated single piles to account for group effects. While O'Neill increases the pile deflection for a particular soil resistance using factors based on Mindlin's flexibility equations, Brown decreases the soil resistance for a particular pile deflection, using factors based on experimental data, for each p-y curve at different depths to account for pile-soil-pile interaction. Brown's factors, called p-multipliers, depend on row position of the pile and the soil type. Both O'Neill's and Brown's models indirectly consider the pile-soil-pile interaction by 'softening' the pile-soil interactions/p-y curves. In this dissertation, a new method which directly and rationally models both pile-soil and pile-soil-pile interactions is proposed. In this new method, FEM is used. First piles are discretized. Then pile-soil interaction is modeled by nonlinear springs representing p-y curves and pile-soil-pile is modeled by linear springs representing Mindlin's flexibilities. Stiffness of the soil mass is calculated by inverting the total flexibility obtained after adding the flexibilities of the pile-soil nonlinear springs and the pile-soil-pile linear springs. Displacement of the pile group system is solved for a lateral loading after

assembling the stiffnesses of the pile elements and the soil mass.

CHAPTER 3
PROGRAM LPG

3.1 Pile Model

The pile group program presented in this dissertation, LPG - Laterally loaded Pile Group, uses a finite element idealization for the pile. This approach breaks up each pile into individual 3-D beam elements as shown in Figure 3.1 One of the elements is depicted in Figure 3.2.

In general there are ten displacement parameters ($dz_j, dx_j, dy_j, \theta x_j, \theta y_j, dz_k, dx_k, dy_k, \theta x_k, \theta y_k$) for each element. The parameters $dz_j, dx_j, dy_j, \theta x_j, \theta y_j$ correspond to displacements at one end of the element and $dz_k, dx_k, dy_k, \theta x_k, \theta y_k$ correspond to the other end. Figure 3.2 shows a 3-D beam element i that is fully restrained at both ends, j and k. Orthogonal element oriented axes also appear in the figure, with the origin located at point j. The z_e axis coincides with the centroidal axis of the member and is positive in the sense from j to k. The x_e-z_e and y_e-z_e planes are principal planes of bending. Let L denote the length of the element, A the area of cross section, Ix and Iy the principal moment of inertia of the cross section of the element with respect to the x_e and y_e axes and E the Young's modulus of the element.

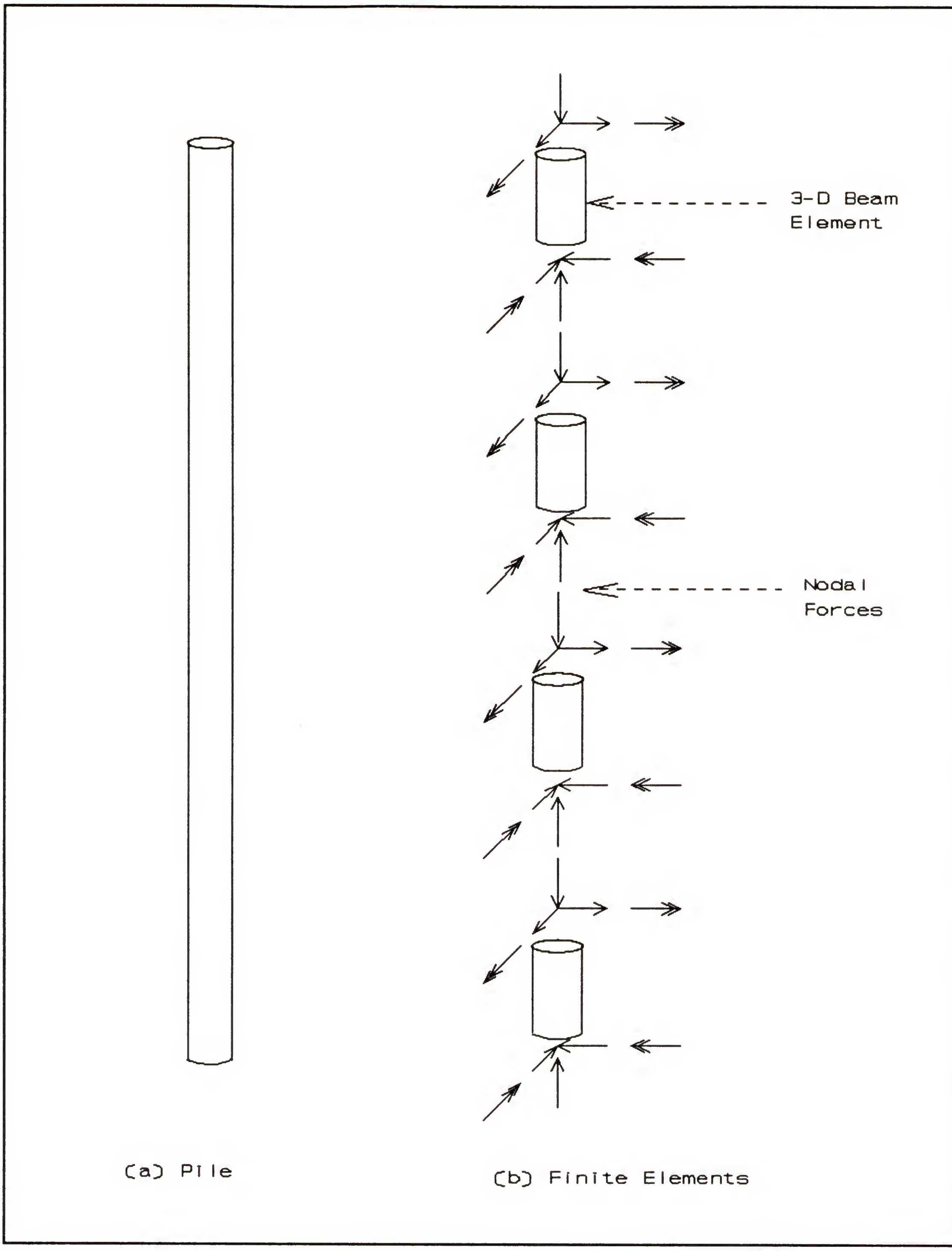
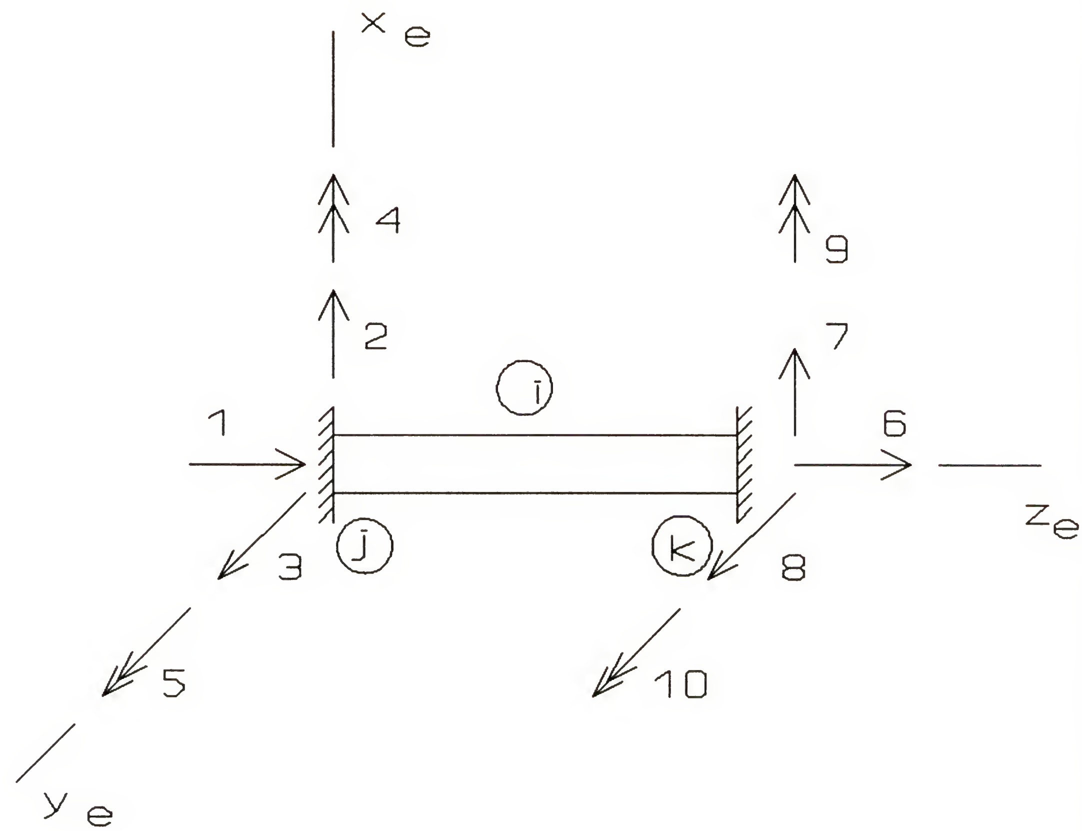


Figure 3.1. Finite Element Idealization of a Pile.



Numbers in figure indicate directions of degrees of freedom of nodes j and k of 3-D beam element i.

Figure 3.2. 3-D Beam Element.

Element stiffnesses for the restrained element shown in Figure 3.2 consist of actions exerted on the element by the restraints when unit displacements (translations and rotations) are imposed at each end of the member. Values of these restraint actions can be obtained from any standard text (for example, Ref. 28). The unit displacements are considered to be induced one at a time while all other end displacements are retained at zero; also, they are assumed to be positive in the x_e,y_e and z_e directions. Thus, the positive senses of the three translations and the two rotations at each end of the element are indicated by arrows in Figure 3.2. In the figure the single-headed arrows denote translations and double-headed arrows represent rotations. The translations and rotations are also called degrees of freedom. At joint j the translations are numbered 1,2 and 3 and the rotations are numbered 4 and 5. Similarly at the k end of the element 6, 7 and 8 are translations and 9 and 10 are rotations. In all cases the displacements are taken in the order z_e, x_e and y_e respectively.

The element stiffnesses for the ten possible types of end displacements (shown in Figure 3.2) are summarized pictorially in Figure 3.3. In each case the various restraint actions or element stiffnesses are shown as vectors. An arrow with a single head represents a force vector, and an arrow with a double head represents a moment vector. All vectors are drawn in the positive senses, but

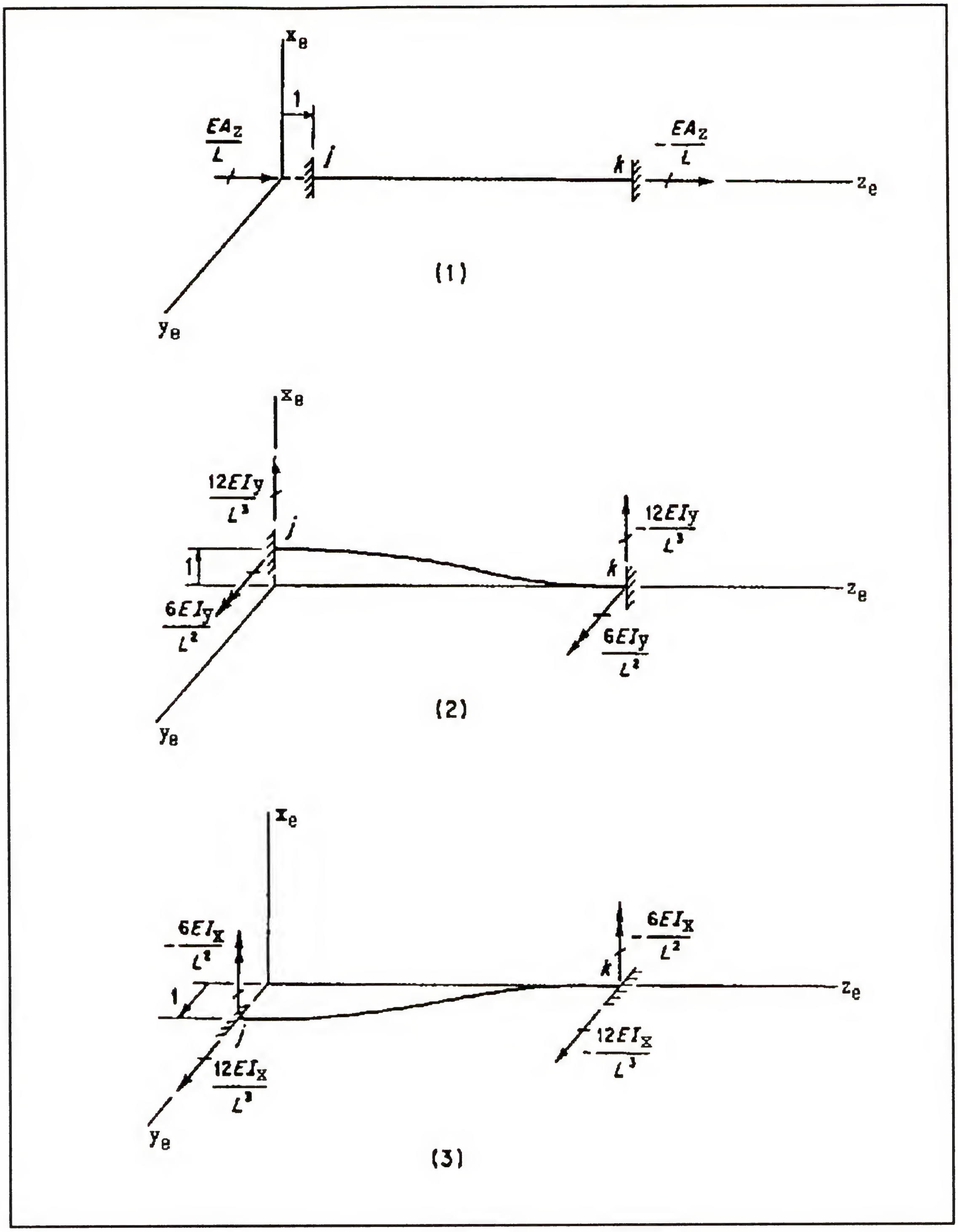


Figure 3.3. Element Stiffnesses.
(Modified after Ref. 28)
(1) Unit ze translation at j;
(2) Unit xe translation at j;
(3) Unit ye translation at j;

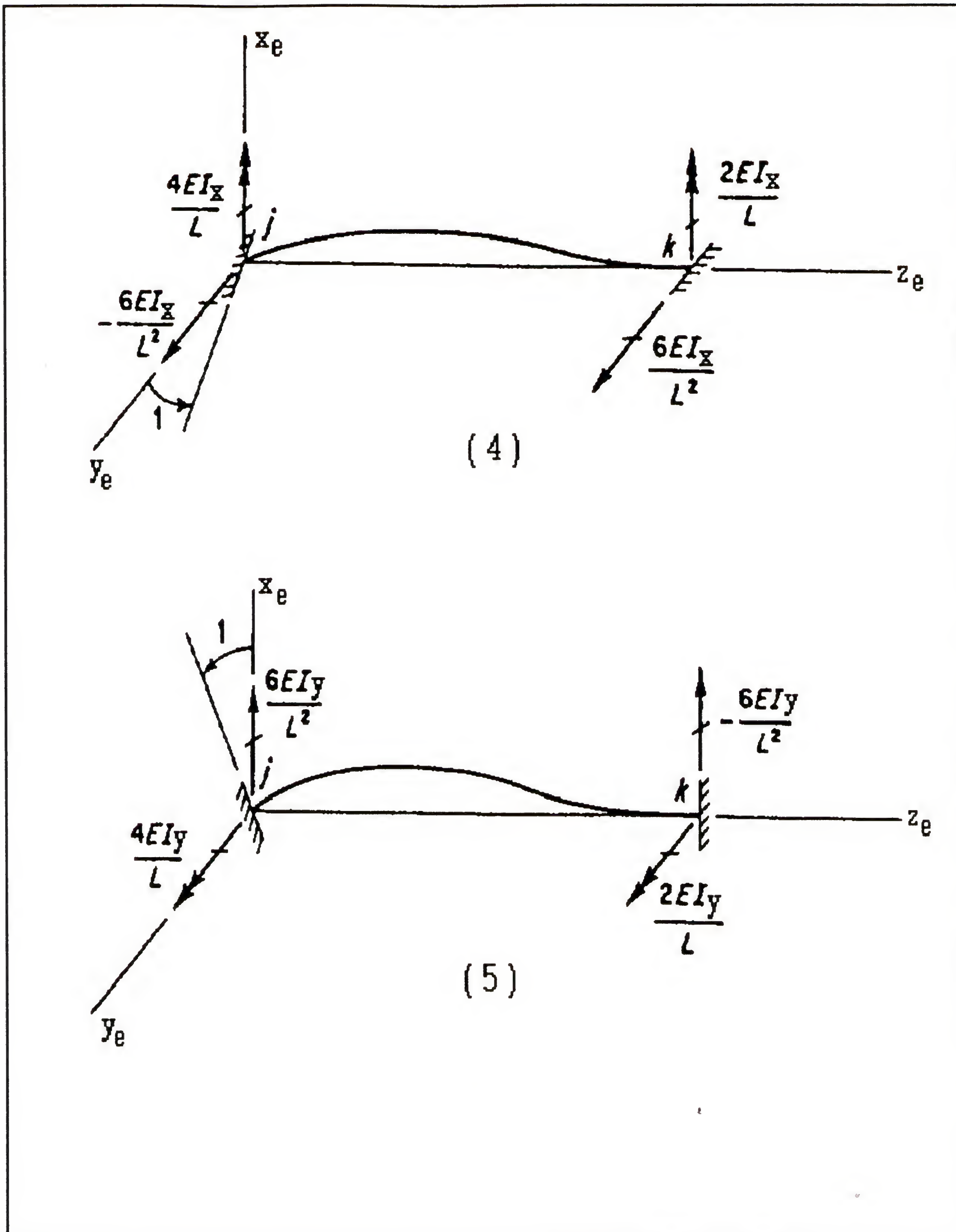


Figure 3.3.--Continued.
(4) Unit xe rotation at j;
(5) Unit ye rotation at j;

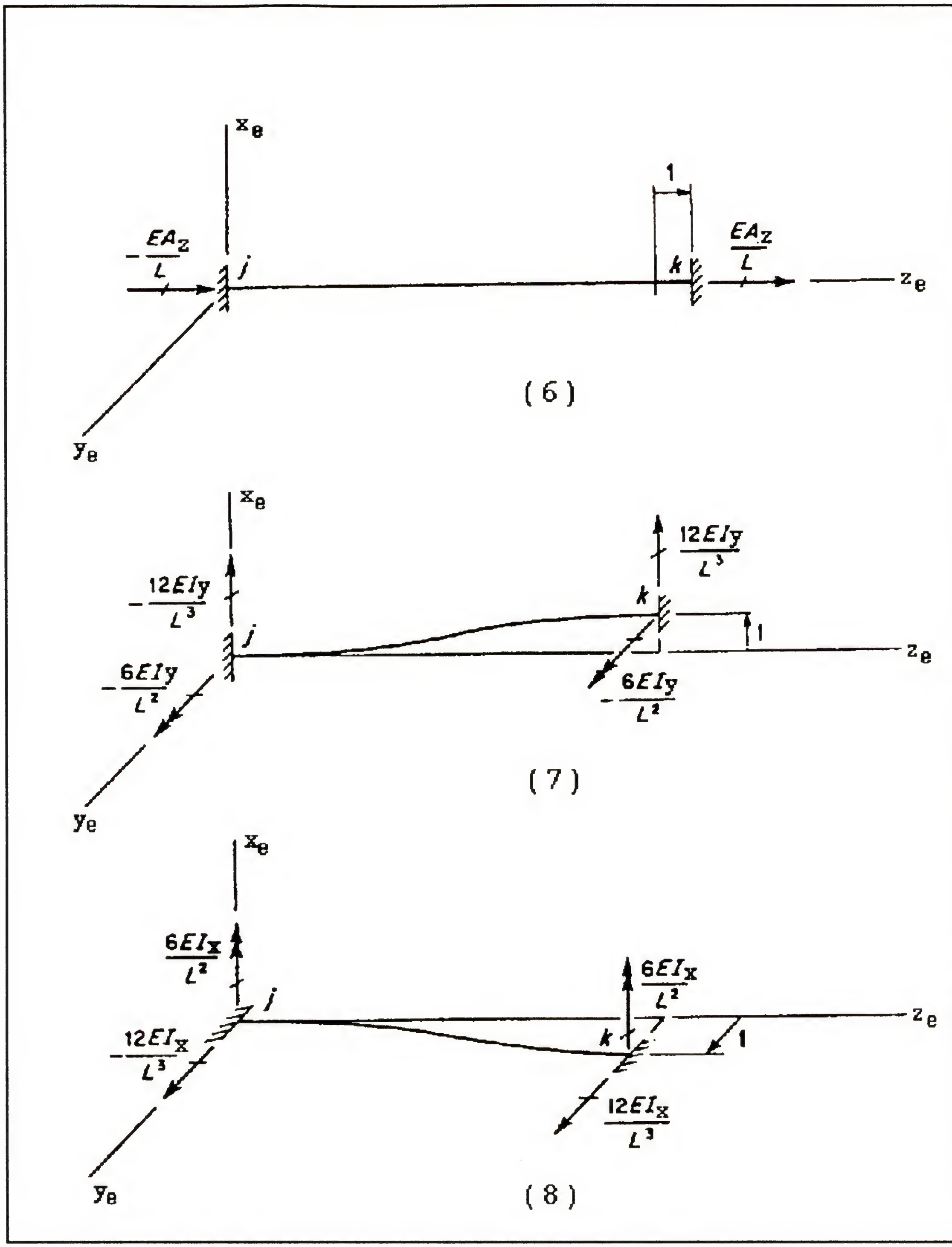


Figure 3.3.--Continued.
(6) Unit z_e translation at k;
(7) Unit x_e translation at k;
(8) Unit y_e translation at k;

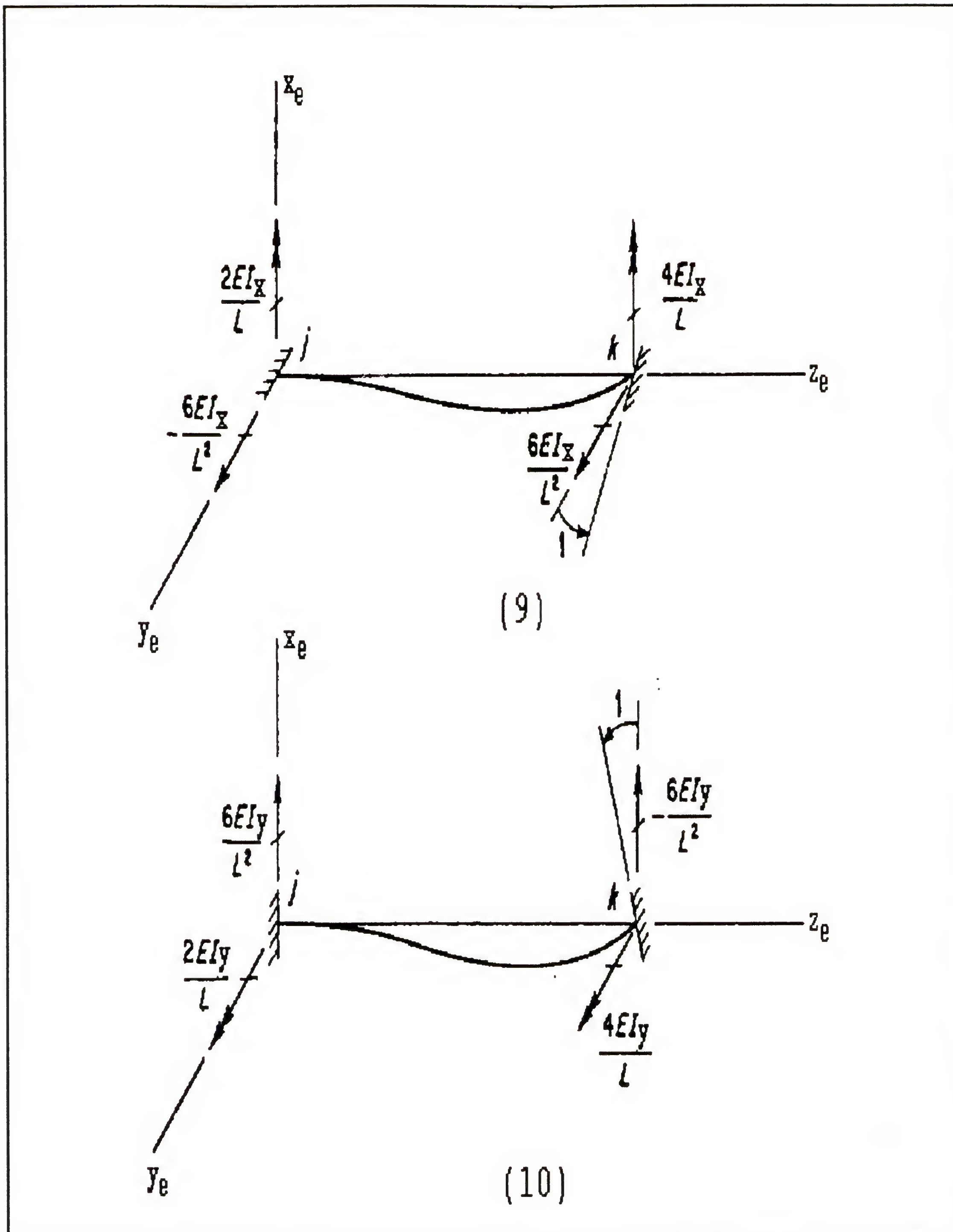


Figure 3.3.--Continued.
(9) Unit x_e rotation at k;
(10) Unit y_e rotation at k.

in cases where the restraint actions are actually negative a minus sign precedes the expression for the stiffness coefficient.

In order to see how the member stiffnesses are determined consider case (1) in Figure 3.3. The restraint actions shown in the figure arise because of a unit translation of the j end of the member in the positive z_e direction. All other displacements are zero. This displacement causes a pure compressive force EA/L in the member.

At the j end of the element this force is equilibrated by a restraint action EA/L in the positive z_e direction and at the k end of the element the restraint action has the same value but is in the negative z_e direction. All other restraint actions are zero in this case.

Case (2) in Figure 3.3 involves a unit translation of the j end of the member in the positive x_e direction, while all other displacements are zero. This displacement causes both moment and shear in the element. At the j end, the restraint actions required to keep the element in equilibrium are a lateral force of $12\ EIy/L^3$ in the positive x_e direction and a moment $6\ EIy/L^2$ in the positive y_e sense. At the k end of the element the restraint actions are the same except that the lateral force acts in the negative x_e direction.

All of the element stiffnesses shown in the figure are derived by determining the values of the restraint actions

required to hold the distorted member in equilibrium. For the pile element used in the program, it is possible for the element to undergo any of the ten displacements shown in Figure 3.3. The stiffness matrix for such a element, denoted k_{pi}, is therefore of order 10 x 10, and each column in the matrix represents the actions caused by one of the unit displacements. The 3-D beam element stiffness matrix is shown in Table 3.1; it is of course symmetrical.
From the element stiffness matrix, one will observe that there is no interaction of axial forces and bending moments, meaning there is no P-δ effect. This element stiffness matrix is used to create stiffness for each pile element of a pile group in the subroutine ELSTFP in the computer program LPG.

3.2 Pile-Soil Interaction

The lateral pile-soil interaction is modelled by nonlinear springs at each node in the pile group. At the tips, in addition to nonlinear springs used to model lateral pile-soil interaction, linear springs are used to model axial pile-soil interaction. Figure 3.4 depicts a single pile broken into four elements with pile-soil springs attached. The ten pile-soil nonlinear springs shown in the figure contributes to lateral resistance in X and Y directions while the vertical pile-soil linear spring contributes to pile tip axial resistance in Z direction.

Table 3.1. 3-D Beam Element Stiffness Matrix.

k_{pi} =

1	2	3	4	5	6	7	8	9	10	
$\frac{AE}{L}$	0	0	0	0	$\frac{-AE}{L}$	0	0	0	0	1
0	$\frac{12EIy}{L^3}$	0	0	$\frac{6EIy}{L^2}$	0	$\frac{-12EIy}{L^3}$	0	0	$\frac{6EIy}{L^2}$	2
0	0	$\frac{12EIx}{L^3}$	$\frac{-6EIx}{L^2}$	0	0	0	$\frac{-12EIx}{L^3}$	$\frac{-6EIx}{L^2}$	0	3
0	0	$\frac{-6EIx}{L^2}$	$\frac{4EIx}{L}$	0	0	0	$\frac{6EIx}{L^2}$	$\frac{2EIx}{L}$	0	4
0	$\frac{6EIy}{L^2}$	0	0	$\frac{4EIx}{L}$	0	$\frac{-6EIy}{L^2}$	0	0	$\frac{2EIy}{L}$	5
$\frac{-AE}{L}$	0	0	0	0	$\frac{AE}{L}$	0	0	0	0	6
0	$\frac{-12EIy}{L^3}$	0	0	$\frac{-6EIy}{L^2}$	0	$\frac{12EIy}{L^3}$	0	0	$\frac{-6EIy}{L^2}$	7
0	0	$\frac{-12EIx}{L^3}$	$\frac{6EIx}{L^2}$	0	0	0	$\frac{12EIx}{L^3}$	$\frac{6EIx}{L^2}$	0	8
0	0	$\frac{-6EIx}{L^2}$	$\frac{2EIx}{L}$	0	0	0	$\frac{6EIx}{L^2}$	$\frac{4EIx}{L}$	0	9
0	$\frac{6EIy}{L^2}$	0	0	$\frac{2EIx}{L}$	0	$\frac{-6EIy}{L^2}$	0	0	$\frac{4EIy}{L}$	10

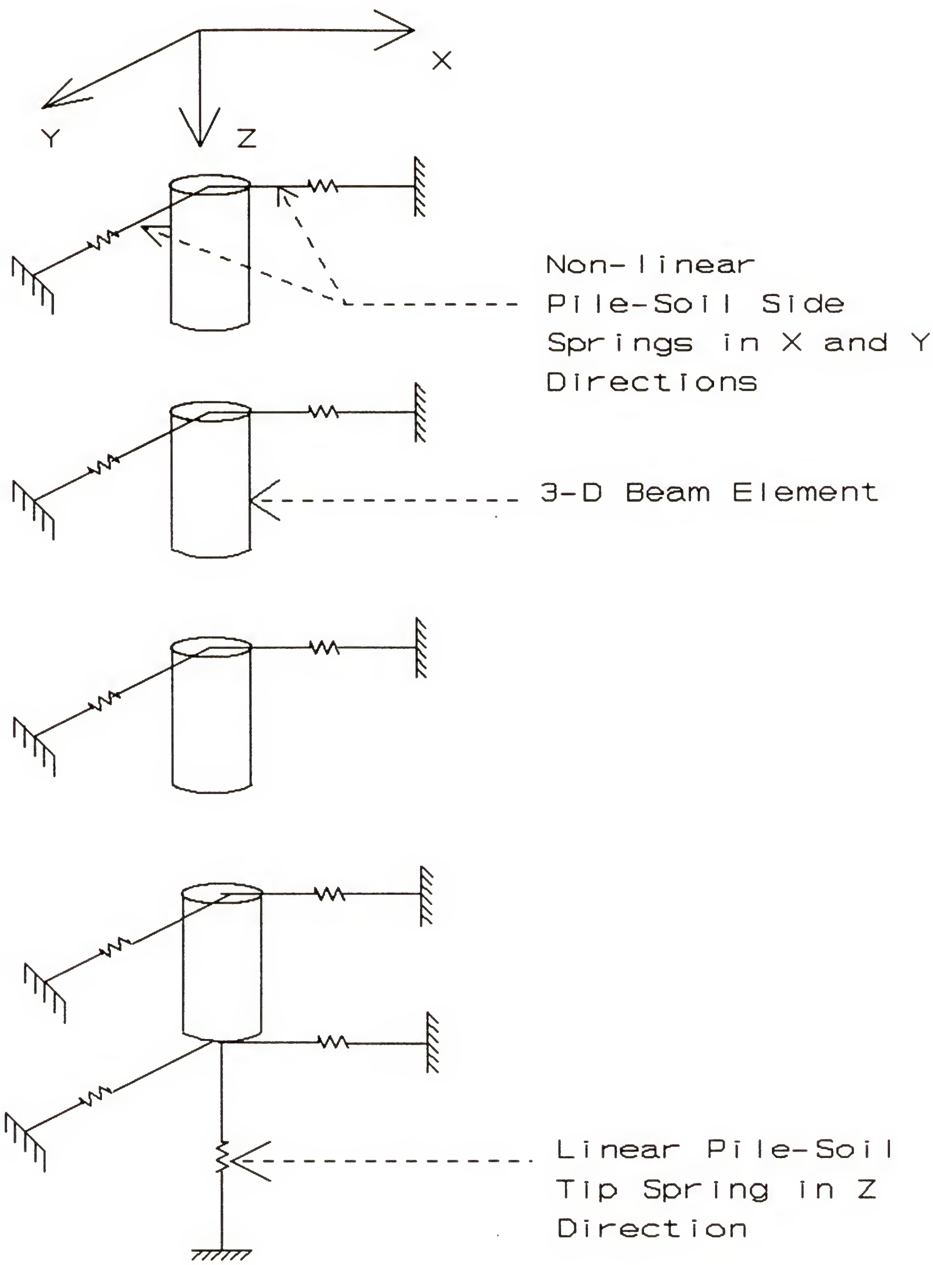


Figure 3.4. Pile-Soil Interaction Model (Side and Tip).

The axes X, Y and Z are global and they are in the same directions as the element or local axes x_e, y_e and z_e.

The vertical springs in Z direction are assumed to be linear with pile tip deflection and their stiffnesses are equal to pile tip soil stiffnesses. The lateral nonlinear springs, technically called p-y curves in the literature where p is the soil resistance and y is the lateral deflection of the pile, depict lateral pile-soil interaction. In this program, O'Neill's p-y curves (6,14) for both cohesionless and cohesive soils and static and cyclic loading are used.

3.2.1 P - Y Curve for Cohesionless Soils

Based on several lateral load tests on single piles, O'Neill (14) proposed the following relationship between the soil resistance p and the lateral deflection of pile y at any depth z in soil from ground surface.

$$p = \eta \, A \, p_u \tanh \left[\left(\frac{kz}{A \, \eta \, p_u} \right) y \right] \qquad \text{... Eqn. 3.1}$$

where η = a factor used to describe pile shape;

= 1.0 for circular piles;

A = 0.9 for cyclic loading;

= 3-0.8 z/D ≥ 0.9 for static loading;

D = diameter of pile;

p_u = ultimate soil resistance per unit of depth;

k = modulus of lateral soil reaction (lb/ft^3 or N/m^3).

The ultimate soil resistance p_u in equation 3.1 is determined from the lesser value given by equations 3.2 and 3.3.

$$p_u = \gamma\ z\ [D\ (K_p - K_a) + z\ K_p \tan\phi \tan\beta\ ] \qquad \ldots \text{ Eqn. 3.2}$$

$$p_u = \gamma\ D\ z\ (K_p^3 + 2\ K_o\ K_p^2 \tan\phi + \tan\phi - K_a) \qquad \ldots \text{ Eqn. 3.3}$$

where z = depth in soil from ground surface;

γ = effective unit weight of soil;

K_a = Rankine active coefficient;

= $(1-\sin\phi)/(1+\sin\phi)$;

K_p = Rankine passive coefficient;

= $1/K_a$;

K_o = at-rest earth pressure coefficient;

= $1-\sin\phi$;

ϕ = angle of internal friction;

$\beta = 45^\circ + \phi/2$.

The p-y relationship in equation 3.1 depends on the soil parameters k (lb/in^3 or N/m^3) and ϕ (deg), which may be obtained from the insitu test SPT. Figure 3.5 gives the correlation of SPT to friction angle ϕ and relative density D_r, and Figure 3.6 gives the correlation of D_r to k.

O'Neill's p-y relationship in equation 3.1 is similar to one suggested by Reese, Cox and Koop (21), which is widely used in the industry. This similarity is shown in Figure 3.7. In the figure, it can be observed that the curves differ only slightly. While the Reese, Cox and Koop's p-y curve is made of four segments, O'Neill's is

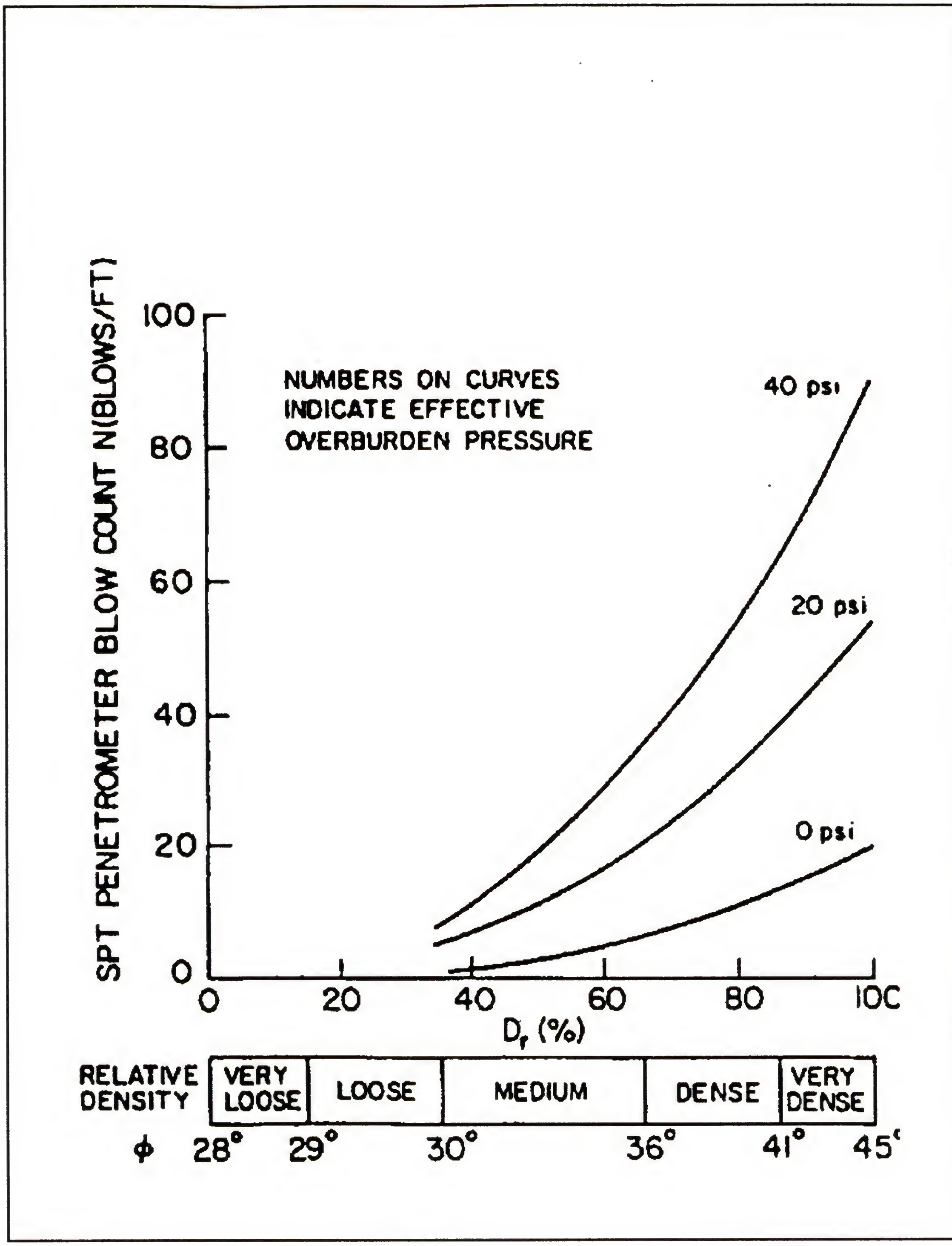


Figure 3.5. SPT Blow Count Vs Friction Angle
and Relative density.
(Modified after Ref. 7)

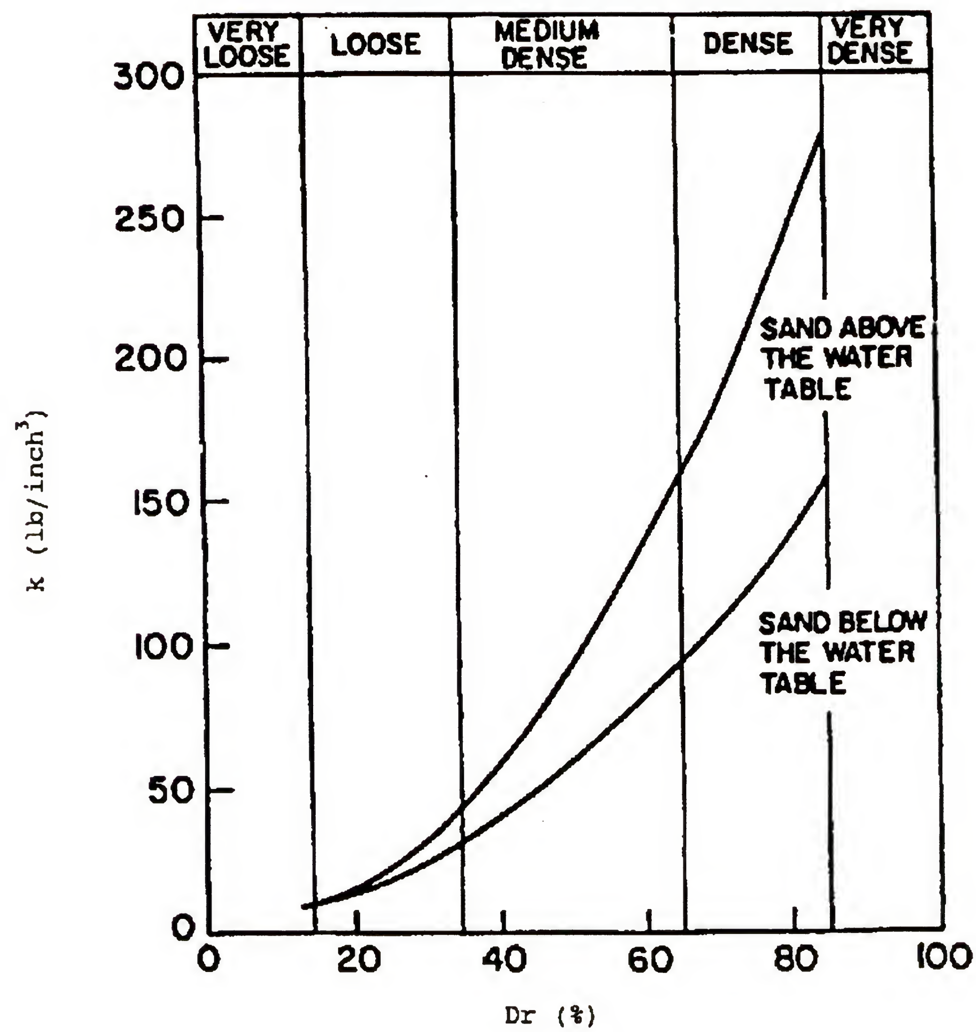


Figure 3.6. k Vs Relative density.
(Modified after Ref. 12)

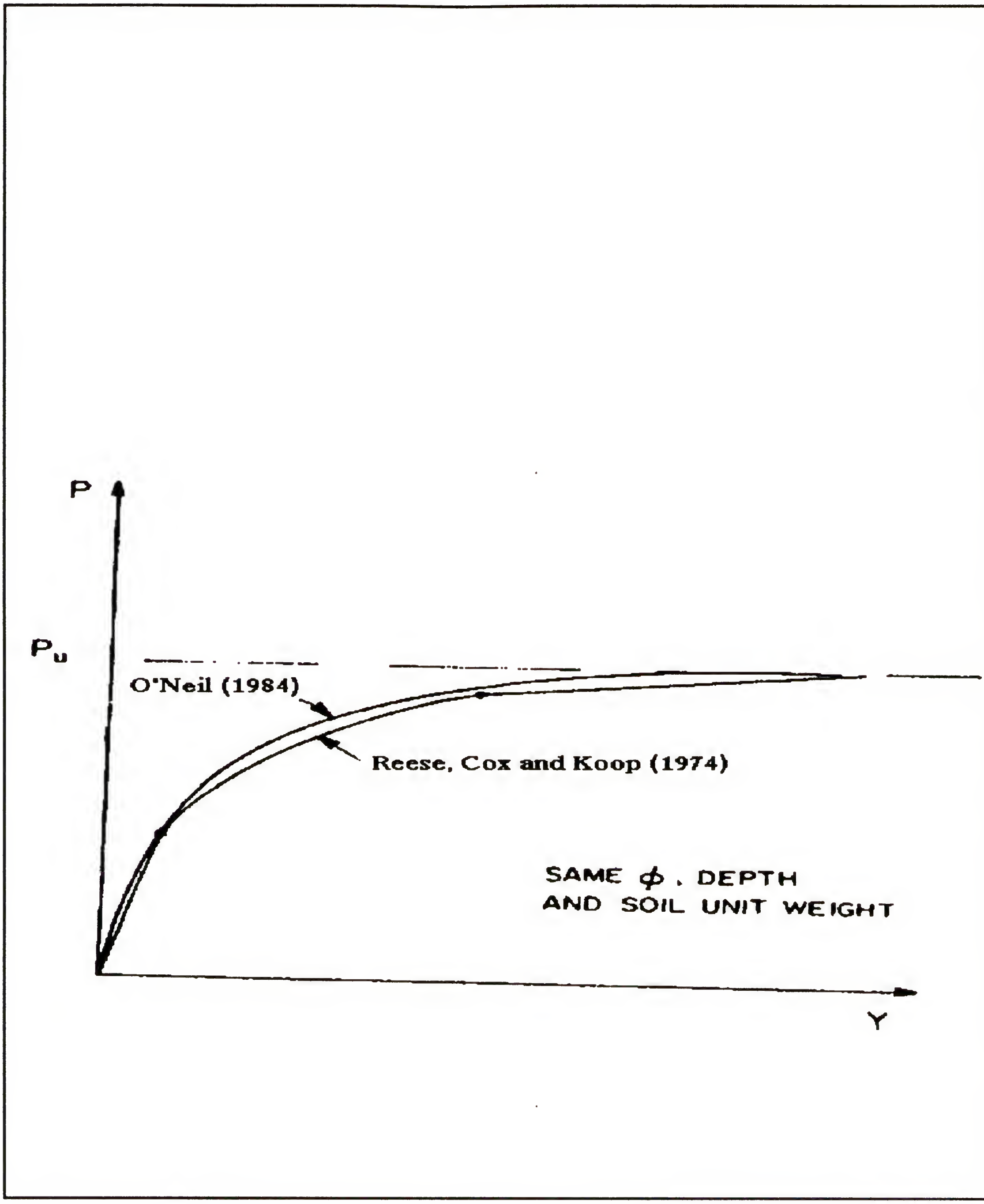


Figure 3.7. Comparison of Shapes of O'Neill's and Reese, Cox and Koop's p-y Curves. (After Ref. 14)

made of only one segment which makes it easier to implement in the computer program LPG.

Initial slopes of p-y curves are used to calculate tangent pile-soil flexibility, the first step in the secant solution scheme (Section 3.4) adopted in this dissertation to solve the nonlinear pile group system equations. Initial slope of a p-y curve both for static and cyclic loading for a cohesionless soil is equal to k*z (lb/in^2 or N/m^2) (Appendix A).

3.2.2 P-Y Curve for Cohesive Soils

The p-y curves suggested previously for cohesive soils fall into two categories. One is soft clay method (11) and the other is stiff clay (22) method. There is also one more unified clay method (26) applicable to all cohesive soils. But it essentially converts to either a stiff-clay-like method or a soft-clay-like method based on the soil parameters chosen by the user. In this dissertation, a new integrated method suggested by O'Neill (6) which is applicable to the response of all cohesive soils, is used.

The p-y relationship for cohesive soils as proposed by O'Neill (6) can be arrived at by the following steps:

(1) Assess critical length of pile, Lc:

$$Lc = 3 \left[\frac{EI}{Es\ D^{0.5}}\right]^{0.286} \qquad \text{... Eqn. 3.4}$$

where EI is the flexural stiffness of the pile;

Es is an operating soil modulus;

D is the diameter of pile.

Es may be assumed as a secant Young's modulus at 50% of failure deviatoric stress in undrained triaxial compression test. O'Neill (6) has suggested values of Es based on correlations with the average UU triaxial compression shear strength between the surface and depth Lc and they are tabulated in Table 3.2. But the author did not get good results using these correlations for predicting the load-deflection response of field load test in Houston, Texas (Section 4.4). So he tried the correlation suggested by Banerjee and Davies (1), given below:

$$Es = 100\ Cu \qquad \text{... Eqn. 3.5}$$

where Es = secant Young's modulus of soil;

Cu = undrained shear strength.

The later correlation produced good results and is used in the computer program LPG.

Table 3.2. O'Neill's Correlation of Es to Cu.

Undrained Shear Strength Cu (psi)	Secant Young's Modulus Es (psi)
< 3.472	50
3.472 - 6.944	50 - 150
6.944 - 13.889	150 - 450
13.889 - 27.778	450 - 1500
27.778 - 55.556	1500 - 5000
> 55.556	5000

Since Es is correlated to shear strength, it will vary with depth, if shear strength varies with depth. In that case Lc has to be assessed iteratively using the equation

3.4. The following procedure is adopted in the subroutine CRITL in the program LPG:

(a) assume Lc = 5 * D;

(b) find average Es between ground surface and depth Lc; The soil in between the ground surface and depth Lc may have both cohesive and cohesionless soils. Es for a cohesive soil is obtained from its correlation to shear strength Cu suggested in equation 3.5. For a cohesionless soil, Es at any depth z in soil below the ground surface is obtained from its modulus of lateral reaction k (lb/in^3 or N/m^3), as given by the following equation (18):

$$\frac{Es}{z} \approx k \qquad \text{... Eqn. 3.6}$$

(c) find Lc,new by equation 3.4 using the average Es calculated in step (b);

(d) find error = abs{(Lc,new -Lc)/Lc,new};

(e) assume Lc = Lc,new;

(f) repeat process (b)-(e) until error $\leq$ tolerance.

(2) Assess reference deflection, yc:

$$y_c = A' \epsilon_{50} D^{0.5} (EI/Es)^{0.125} \qquad \text{... Eqn. 3.7}$$

where Es = value of soil modulus corresponding to shear strength at depth of interest using the correlation suggested in equation 3.5;

A' = 0.8, a constant;

ϵ_{50} = Major principal strain at 50% maximum deviator stress in a UU triaxial compression test.

(3) Formulate ultimate soil resistance, p_u:

p_u = F Np Cu D ... Eqn. 3.8

where F = a reduction factor from Table 3.3 based on soil ductility and form of loading (static or cyclic);

Cu = the undrained shear strength;

Np = 3 + 6 $(z/z_{cr}) \leq 9$; ... Eqn. 3.9

z_{cr} = Lc/4 and ... Eqn. 3.10

z = depth from ground surface in soil.

Table 3.3. Soil Degradability Factor, F.

Factor	UU triaxial compression failure strain, ϵ_{100}		
	< 0.02	0.02 - 0.06	> 0.06
Fstatic	0.50	0.75	1.00
Fcyclic	0.33	0.67	1.00

(4) Construct the p-y curves:

Figure 3.8 describes graphically the construction of static and cyclic p-y curves using the O'Neill's Method (6).

Initial slopes of p-y curves, as mentioned elsewhere, are used in the secant solution scheme (Section 3.4) adopted in this dissertation, to start the solution procedure. The initial slope of a p-y curve for a cohesive soil, both for static and cyclic loading, is infinity (Appendix A). So a finite value has to be implemented in the program LPG for the slope. This finite value can be any large number and final result obtained for nonlinear pile group system equations, after convergence using the secant solution scheme (Section 3.4), does not depend on this initial finite

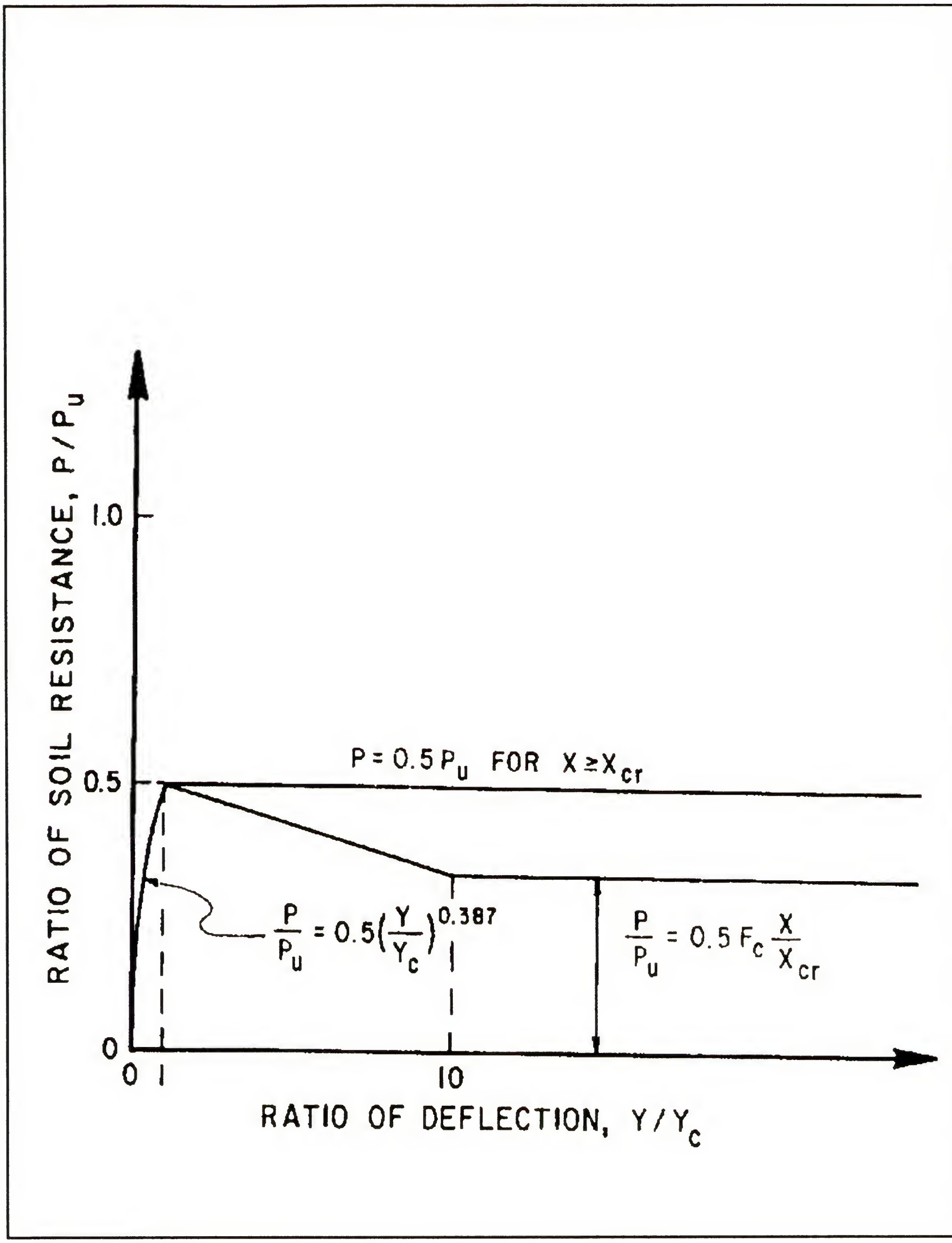


Figure 3.8. Construction of p-y Curve by O'Neill's Integrated Clay method (After Ref. 6).
(a) Static Loading case;

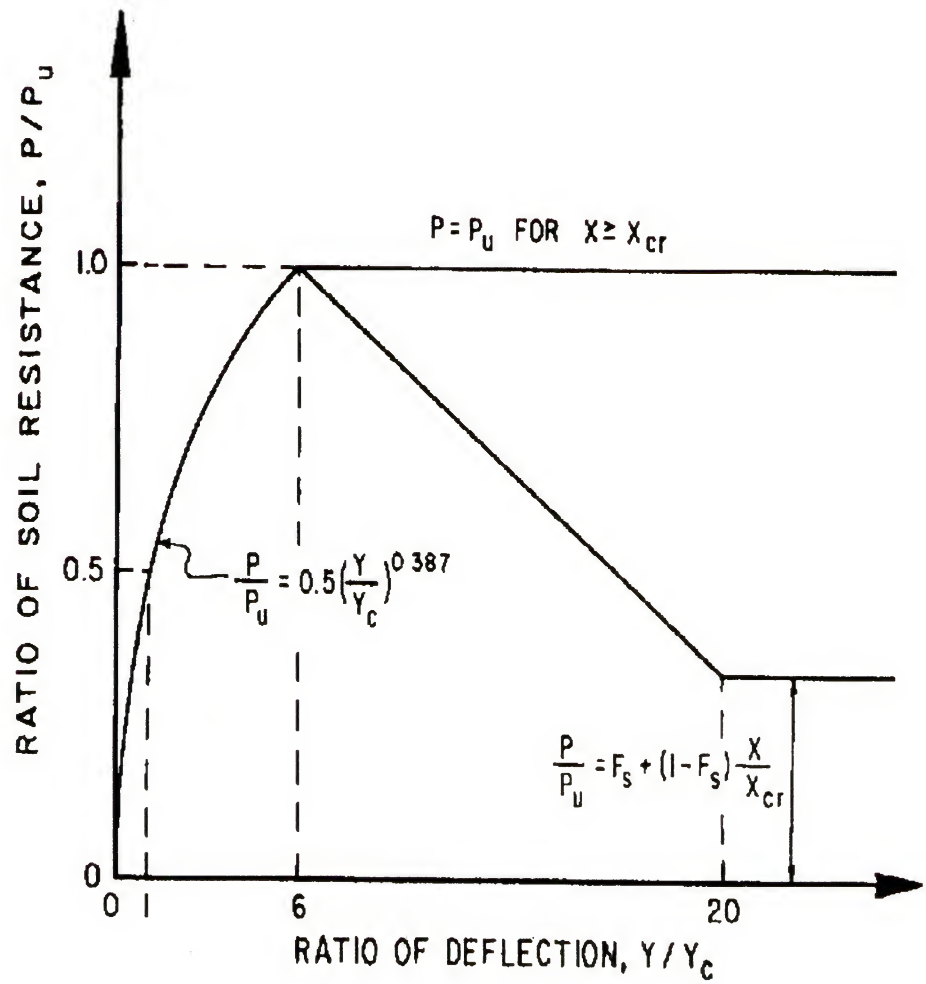


Figure 3.8.--Continued.
(b) Cyclic Loading case.

value for the slope. A value equal to the soil modulus Es used in the p-y curve is also used for the initial slope of the p-y curve for cohesive soil in the program LPG.

3.3 Pile-Soil-Pile Interaction

The pile group program presented in this dissertation considers interaction between piles directly. In determining that interaction, it is necessary to convert the distributed lateral load along the pile shaft and pile base into point loads acting at the pile nodes. The influence between piles is then characterized through flexibility coefficients $f_{ix,jx}$, $f_{iy,jx}$, $f_{ix,jy}$ and $f_{iy,jy}$, based on Mindlin's solution (13) for lateral point loads applied in X and Y directions in a homogeneous, isotropic elastic half-space. The flexibility term $f_{ix,jx}$ represents displacement at node i in X direction from unit force applied to node j in X direction. Similarly the term $f_{iy,jx}$ represents the displacement at node i in Y direction from the unit force applied to node j in X direction. The terms $f_{ix,jy}$ and $f_{iy,jy}$ could also be defined similarly. It should be noted that the coefficients $f_{ix,jx}$, $f_{iy,jx}$, $f_{ix,jy}$ and $f_{iy,jy}$ are zero if i and j are on the same pile (they are modelled through pile-soil interaction). Figures 3.9 and 3.10 are provided to explain this further. Figure 3.9 is a two-pile group with five nodes and four elements per pile. Node 1 is not affected by node 2 (modelled through pile-soil interaction) but it is influenced by forces generated both in X and Y direction at

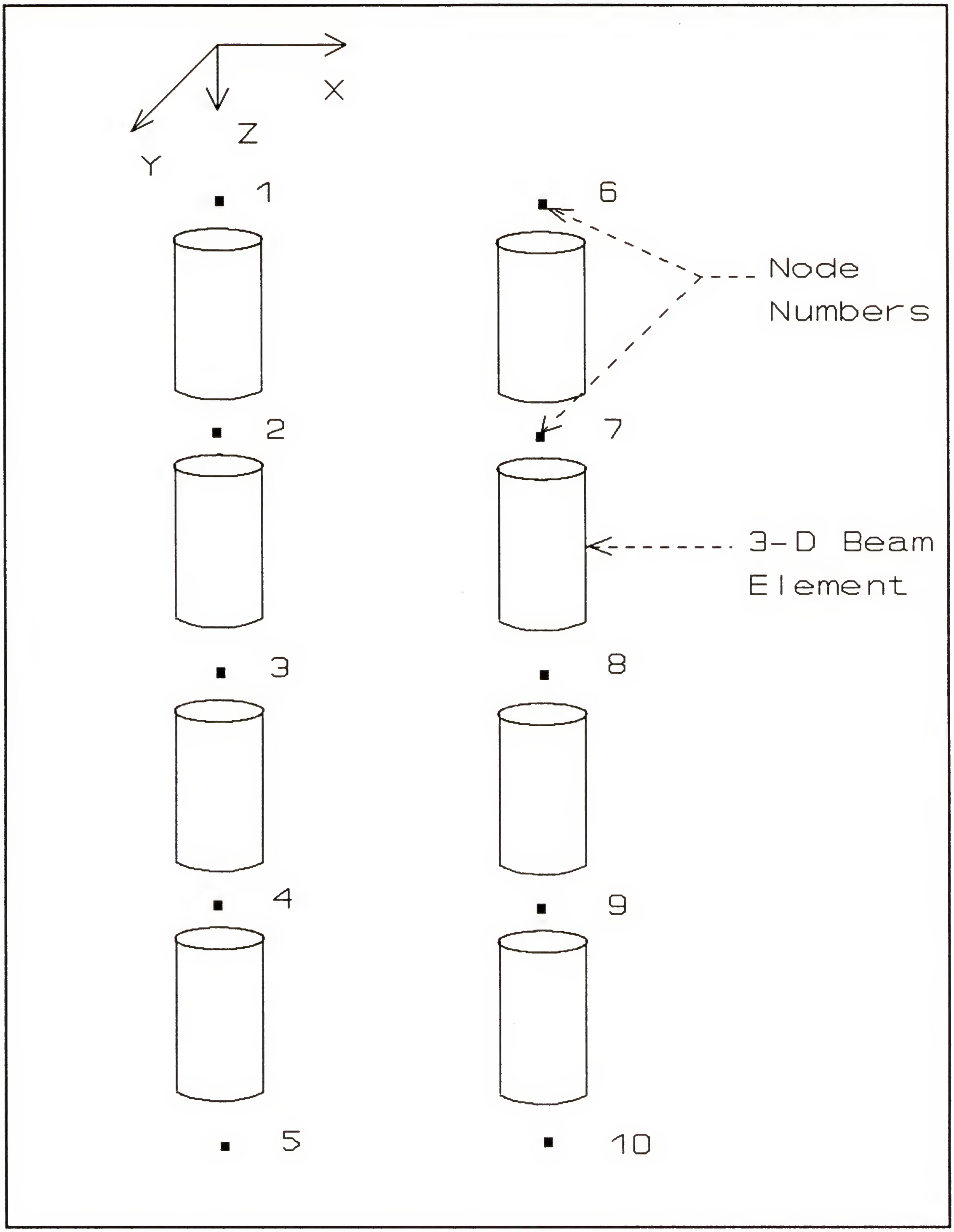


Figure 3.9. Element Discretization for a Two-Pile Group.

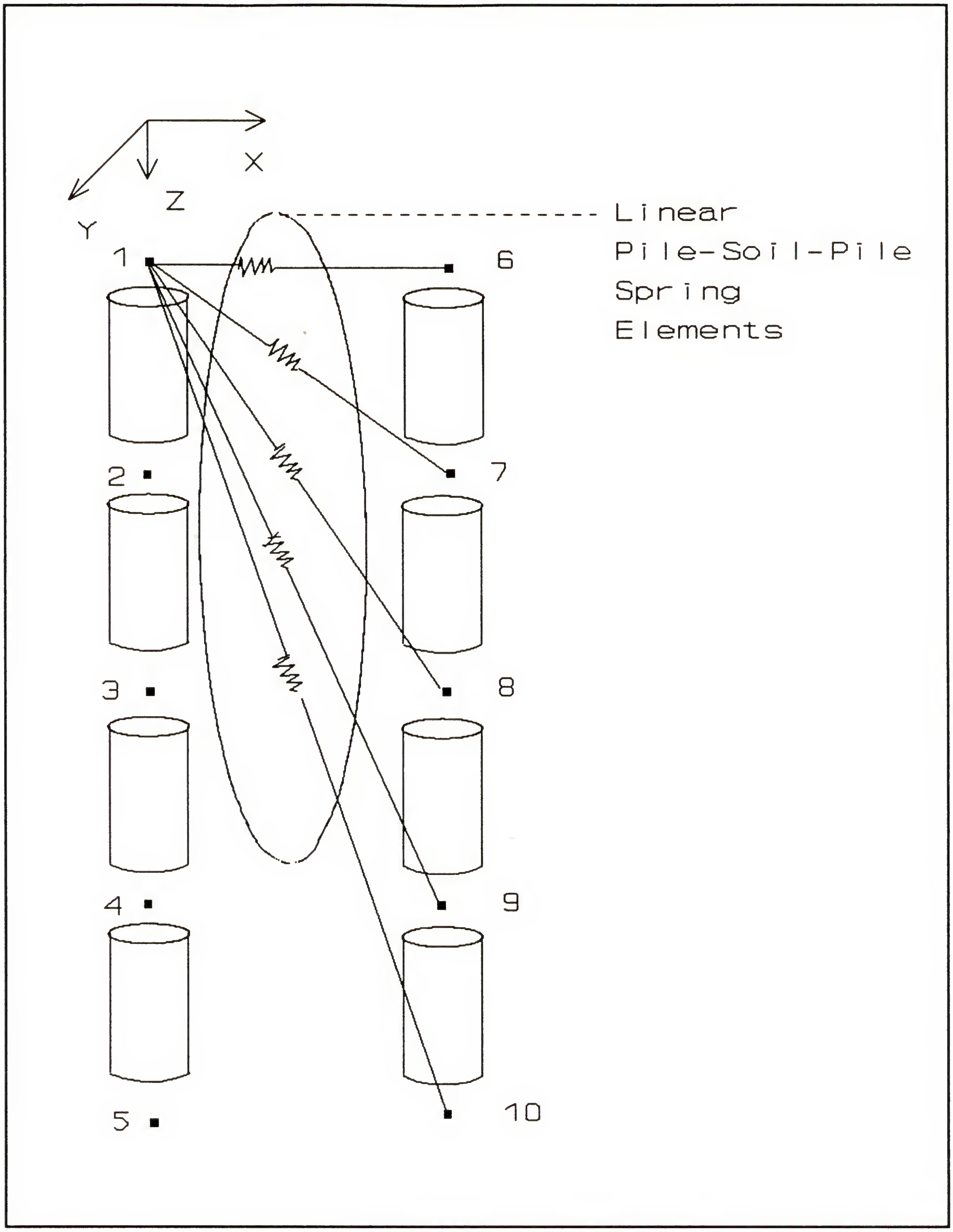


Figure 3.10. Pile-Soil-Pile Linear Spring Characterization.

nodes 6 through 10, due to pile-soil-pile interaction. This influence on node 1 may be represented (Figure 3.10) by linear springs connecting nodes 6 through 10. It should be noted that total 20 linear springs, 4 springs: $f_{ix,jx}$, $f_{iy,jx}$, $f_{ix,jy}$ and $f_{iy,jy}$ each, are connecting nodes 1,6; 1,7; 1,8; 1,9 and 1,10. In the same manner nodes 2 through 10 would be affected. The entire interaction can be represented as a matrix. Each flexibility term in the matrix is determined from Mindlin's equations (13):

$$f_{ix,jx} = \frac{1}{16\,\pi\,G\,(1-\mu)}\left[\frac{(3-4\mu)}{R_1} + \frac{1}{R_2} + \frac{x^2}{R_1^3} + \frac{(3-4\mu)\,x^2}{R_2^3} + \frac{2\,c\,z}{R_2^3}\left(1 - \frac{3\,x^2}{R_2^2}\right) + \frac{4\,(1-\mu)\,(1-2\mu)}{(R_2+z+c)}\left(1 - \frac{x^2}{R_2\,(R_2+z+c)}\right)\right] \quad \text{... Eqn. 3.11}$$

$$f_{iy,jx} = \frac{x\,y}{16\,\pi\,G\,(1-\mu)}\left[\frac{1}{R_1^3} + \frac{(3-4\mu)}{R_2^3} - \frac{6\,cz}{R_2^5} - \frac{4\,(1-\mu)\,(1-2\mu)}{R_2\,(R_2+z+c)^2}\right] \quad \text{... Eqn. 3.12}$$

$$f_{ix,jy} = f_{iy,jx} \quad \text{... Eqn. 3.13}$$

$$f_{iy,jy} = \frac{1}{16\,\pi\,G\,(1-\mu)}\left[\frac{(3-4\mu)}{R_1} + \frac{1}{R_2} + \frac{y^2}{R_1^3}\right.$$

$$+ \frac{(3-4\mu)\ y^2}{R_2^{\ 3}} + \frac{2\ c\ z}{R_2^{\ 3}} \left(1 - \frac{3\ y^2}{R_2^{\ 2}}\right)$$

$$+ \frac{4\ (1-\mu)\ (1-2\mu)}{(R_2+z+c)} \left(1 - \frac{y^2}{R_2\ (R_2+z+c)}\right)] \qquad \text{... Eqn. 3.14}$$

where z = depth coordinate of node i;

ix, iy = node i where the displacement is evaluated in X and Y directions respectively;

jx, jy = node j at which load is applied in X and Y directions respectively;

c = depth coordinate of node j;

μ = Poisson's ratio of media between piles;

G = Shear modulus of media between piles. This is a constant value that must be input into the program. A spatial average of shear moduli along the sides of the pile may be used for this value;

$R_1 = [r^2+(z-c)^2]^{0.5}$;

$R_2 = [r^2+(z+c)^2]^{0.5}$;

$r = [x^2+y^2]^{0.5}$;

x and y = spatial distances on the ground surface between the two piles of interest.

In the example two-pile group shown in Figure 3.9, the matrix would be 20 x 20, where 20 is the total number of degrees of freedom. The flexibility coefficients $f_{ix,jx}$, $f_{iy,jx}$, $f_{ix,jy}$ and $f_{iy,jy}$ would be evaluated for each position in the matrix. The resulting flexibility matrix is then used

in the compilation of the total soil stiffness. The later is accomplished by adding the pile-soil interaction, discussed in the previous section, to pile-soil-pile flexibility to create the total flexibility. This resulting soil flexibility matrix is inverted to give the complete soil stiffness matrix. The soil stiffness matrix is then assembled together with the individual pile stiffness matrices to yield the total group stiffness matrix. The assembled force-displacement relationship for the pile group system is

$$\{f_{ex}\} = [K] * \{w\} \qquad \text{... Eqn. 3.15}$$

where $\{f_{ex}\}$ = external force vector;

$[K]$ = total stiffness for the pile group;

$\{w\}$ = displacement vector for the pile group.

Depending on the subroutine used in solving the equation 3.15 and inverting the soil flexibility matrix, two versions of the program LPG were created. In one version, called PROFILE version, the total global stiffness matrix [K] is stored in a profile form (Section 3.5) and a profile equation solver SUBSOL is used to solve the equation. In the other version, called LU version, [K] is stored in its full matrix form and LU (Section 3.5) decomposition and back-substitution routines LUDCMP and LUBKSB are used to solve the equation. The procedure that the program follows is better explained through the detailed flow chart given in Figure 3.11. Thirty-four steps are depicted in the flow chart and are described in list given below.

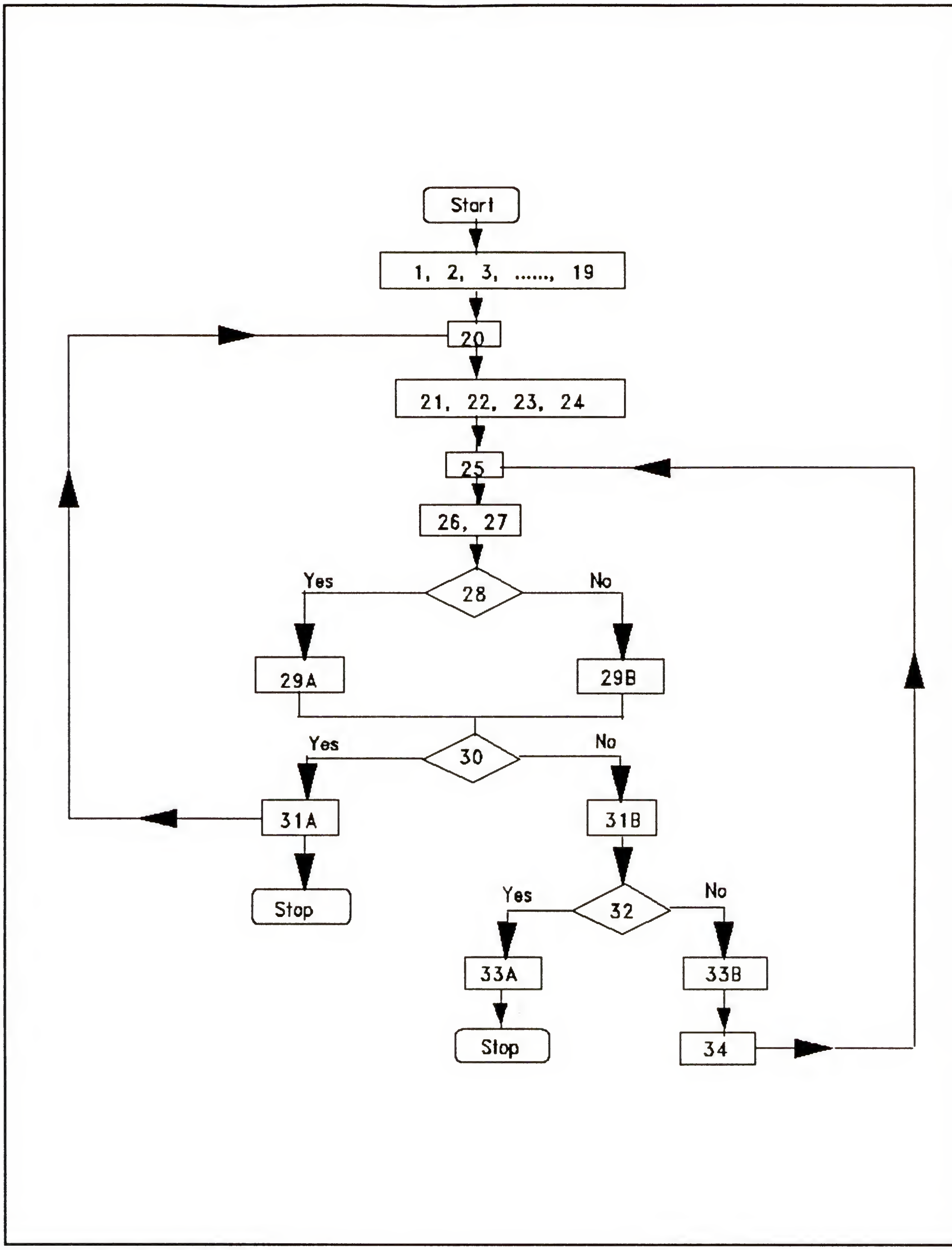


Figure 3.11. Flow Chart of the Program LPG.

LIST OF DESCRIPTIONS OF THE STEPS IN FIGURE 3.11.

STEP#	DESCRIPTION
(1)	Create a big array for dynamic memory storage allocation of all other arrays.
(2)	Initialize critical length CL = 0. This initialization is required for calculating p-y spring forces in step #31-A-(iv).
(3)	Open one input file in unit NUI and three output files in units NUO1, NUO2 and NUO3. Output files in units NUO2 and NUO3 are temporary and they will be deleted after the execution of the program.
(4)	Read data from input file in unit NUI.
(5)	Compute coordinates of each node in pile group.
(6)	For PROFILE version of the program, create NA array for Mindlin's pile-soil-pile flexibility matrix. For LU version, skip this step.
(7)	Compute pile-soil-pile flexibility according to Mindlin's solution.
(8)	Write pile-soil-pile flexibility matrix to the temporary file in unit NUO3.
(9)	Create location matrix for soil stiffness matrix.
(10)	For PROFILE version of the program, create NA array for global stiffness matrix using the location matrix created in the previous step. For LU version, skip this step.

STEP#	DESCRIPTION
(11)	Zero global stiffness matrix.
(12)	Create local element stiffnesses for top and other fifteen elements on each pile in the group. In this program, each pile in the group is divided into 16 elements and length of top element may be different from the other fifteen elements depending on free length of the pile group above ground surface.
(13)	Create location matrices for all pile elements of the group and write them to the temporary file in unit NUO2.
(14)	Assemble all pile element local stiffnesses into the global stiffness matrix using their location matrices.
(15)	Incorporate force or displacement boundary conditions by modifying the global stiffness matrix and external force vector.
(16)	Incorporate the axial soil resistance of pile tips into the global stiffness matrix.
(17)	Write the global stiffness matrix, without the soil stiffness assembled, into the temporary file in unit NUO3.
(18)	Create initial stiffness of the soil by inverting initial soil flexibility matrix. The initial soil flexibility matrix is created by adding initial

STEP#	DESCRIPTION
	pile-soil flexibilities in the diagonal of pile-soil-pile flexibility matrix created in step #7. The initial pile-soil flexibilities are obtained from the reciprocals of initial slopes of p-y curves.
(19)	Assemble the soil stiffness matrix into the global stiffness matrix using its location matrix calculated in step #9.
(20)	Increment loop for external force/displacements applied at top of piles.
(21)	Zero external force vector.
(22)	Zero old displacement vector.
(23)	Calculate external force vector for current increment in step #20.
(24)	Initialize convergence flag ICON = 0.
(25)	Increment iteration loop.
(26)	Solve the system $\{f_{ex}\} = [K] * \{w\}$ for $\{w\}$, the displacement vector.
(27)	Calculate error in displacements by finding absolute maximum difference between the displacement vector calculated in step #26 and the old displacement vector.
(28)	Check if iteration $\neq 1$ and error in displacements $\leq$ prescribed tolerance.

STEP#	DESCRIPTION

(29-A)	If yes, make flag ICON = 1. Go to step #30.
(29-B)	If no, continue.
(30)	Check if flag ICON = 1
(31-A)	If yes,
(i)	Rewind the temporary file in unit NUO3.
(ii)	Read Mindlin's pile-soil-pile flexibility matrix from the temporary file in unit NUO3.
(iii)	Read global stiffness matrix, without the soil stiffness matrix assembled, from the temporary file in unit NUO3.
(iv)	Calculate secant soil stiffness by inverting secant soil flexibility. The secant soil flexibility is obtained from adding secant pile-soil flexibilities in Mindlin's pile-soil-pile flexibility matrix obtained in step 31-A-(ii). The secant pile-soil flexibilities are calculated by dividing local displacements of pile nodes in soil by corresponding p-y spring forces. The local displacements of pile nodes in soil are obtained from the displacement vector, calculated in step #26, using the location matrix for the soil stiffness matrix.
(v)	Assemble secant soil stiffness into the global stiffness using the location matrix for soil stiffness.

STEP#	DESCRIPTION
(vi)	Calculate out-of-balance forces by finding the difference in internal and external forces. Internal forces are obtained from multiplying total global stiffness calculated in previous step, by displacements calculated in step #26.
(vii)	Output converged displacements (step #26), out-of-balance forces (31-A-vi) and forces in all pile elements and soil springs (both near-field and far-field) into the file in unit NUO1. Pile elements' forces are retrieved by multiplying their local stiffnesses by local pile element displacement vectors. Local displacement vectors of all pile elements are obtained from the displacement vector, calculated in step #26, using the location matrices for pile element stiffnesses stored in the temporary file in unit NUO2 (step #13). Similar to pile elements' forces retrieved from pile element stiffnesses, soil springs' forces are retrieved from local secant soil stiffness calculated in step 31-A-iv.
(viii)	Go to step #20.
(31-B)	If no, continue.
(32)	Check if iteration = max iteration.
(33-A)	If yes, stop the execution of program.
(33-B)	If no, continue.

STEP#	DESCRIPTION

(34)

(i)-(v) Same as steps 31-A (i)-(v)

(vi) Copy displacement vector calculated in step #26 into the old displacement vector.

(vii) Go to step #25.

3.4 Solution Strategy

The solution approach used herein is the secant stiffness. To begin the process, the global secant stiffness [K] must be assembled; and the external force vector $\{f_{ex}\}$ is determined. The force-displacement relationship is the one given in equation 3.15.

$$\{f_{ex}\} = [K] * \{w\} \qquad \ldots \text{ Eqn. } 3.15$$

To solve for the nodal displacements, {w}, the global stiffness must be inverted and post-multiplied by the external force vector. The solution strategy is depicted in Figure 3.12. A tangent stiffness is employed for the first step; from the computed displacements and given p-y curves, a new secant flexibility is obtained; using this new flexibility a global stiffness is computed; and finally, employing the original external force vector, a new set of displacements are calculated which allows the process to be repeated until the computed displacements are almost the same as those used in the secant flexibilities. Internal forces are then retrieved by post multiplying the final

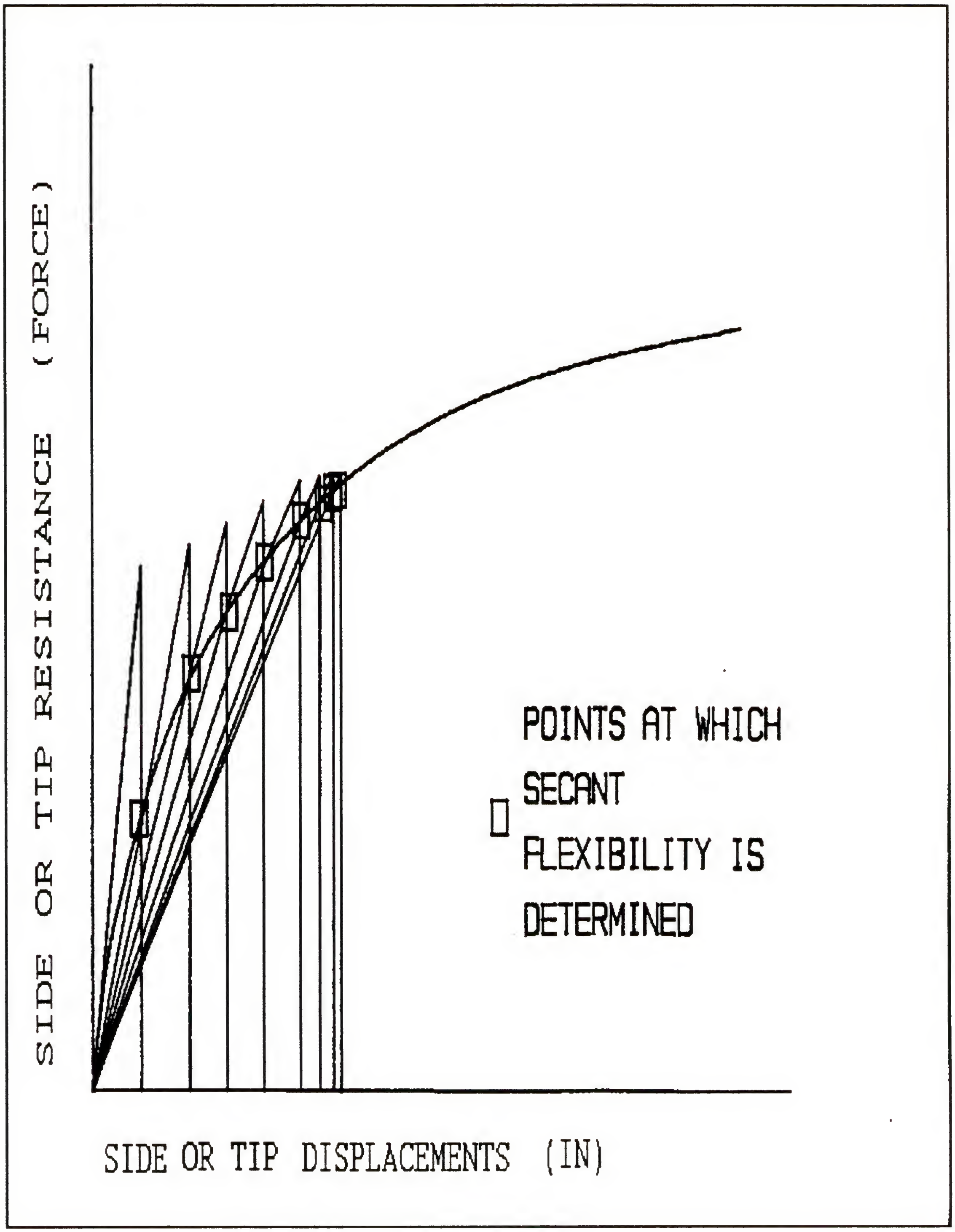


Figure 3.12. Secant Solution Strategy.

secant global stiffness of soil by the final converged displacement vector. The out-of-balance force vector is calculated by finding the difference in external and internal force vectors. The secant solution procedure is outlined below.

Given:

$[K]_j$ = Global secant stiffness of pile elements and soil for iteration j;

$[Kp]$ = Pile elements stiffness (constant) ;

$= \sum_{i=1}^{n} k_{pi}$, n = total number of pile elements;

$[Fm]$ = Mindlin flexibility for pile-soil-pile interaction (constant);

$[Ft]$ = Tangent pile-soil flexibility obtained from initial slopes of p-y curves (constant);

$[Fs]_j$ = Nonlinear secant pile-soil flexibility obtained from p-y curves (O'Neill) (not constant) for iteration j;

$\{w\}_j$ = displacement vector for iteration j;

$\{f_{ex}\}$ = external force vector;

$\{f_{in}\}$ = internal force vector;

$\{f_{ob}\}$ = out-of-balance force vector;

Tolerance = Minimum error on displacements prescribed by user of the program LPG.

Steps:

(1) For iteration j = 1, assume

$[Fs]_j = [Ft]$ and

for iteration $j \neq 1$, calculate

$[Fs]_j$ using $\{w\}_{j-1}$;

(2) For iteration j, calculate

$[K]_j = [Kp] + [\ [Fm] + [Fs]_j\ ]^{-1}$;

(3) For iteration j, calculate

$\{w\}_j = [K]_j^{-1} * \{f_{ex}\}$;

(4) For iteration j, calculate

$\{\delta w\}_j = \{w\}_j - \{w\}_{j-1}$ for $j \neq 1$ and

$\{\delta w\}_j = \{w\}_j$ for $j=1$;

(5) For iteration j, calculate

error = abs max $\{\delta w\}_j$;

(6) Repeat process (1)-(5) until error $\leq$ Tolerance; let jf be the final iteration for which the displacements have converged;

(7) Calculate

(a) $[Fs]_{jf+1}$ using $\{w\}_{jf}$ and

(b) $[K]_{jf+1} = [Kp] + [\ [Fm] + [Fs]_{jf+1}\ ]^{-1}$;

(8) Retrieve internal forces

$\{f_{in}\} = [K]_{jf+1}\ \{w\}_{jf}$;

(9) Calculate out-of-balance forces

$\{f_{ob}\} = \{f_{in}\} - \{f_{ex}\}$.

3.5 Program Optimization

To efficiently use computer memory needed to run the program LPG, a dynamic memory storage allocation method is implemented in its source code. This allocation sets

dimensions of all arrays needed to analyze a pile group problem at the time of execution. It also stores all the arrays in a single big array called A(MTOT). The size of the big array is defined by the size parameter MTOT at beginning of the main routine of the program source code. The big array A(MTOT) is stored at a specific location, the address of named common block COMMON/BIG/, in the memory.

It was observed that major portion of time in running the program is spent on inverting the soil flexibility matrix to obtain the soil stiffness matrix and solving the simultaneous equations (Eqn. 3.15) to obtain displacements. After careful analysis, two methods were contemplated to optimize on the run time. One is incorporating an efficient equation solver and the other is reducing the size of the pile group problem by using symmetry of pile group geometry. Accordingly two versions of the program, PROFILE (Appendix C) and LU (Appendix D) were created.

In PROFILE version, a profile equation solver (also called active column equation solver) SUBSOL is used to solve the simultaneous equations and invert the soil flexibility matrix. This equation solver requires the two matrices, the global stiffness matrix of the simultaneous equations and the soil flexibility matrix, to be stored in two compact vectors. For example, in the vector GLK(NGT) all non-zero right-off-diagonal and diagonal entries of the global stiffness matrix are stored compactly. This type of compactly storing profile of non-zero entries of a matrix

into a vector is called profile storage (8). The entry in the vector GLK corresponding to any entry in the global stiffness matrix can be located by the algorithm of the equation solver (8). Using this type of profile storage is very efficient in saving a considerable amount of computer memory and time for computations.

In LU version, a matrix decomposition method LU is employed. In the LU matrix decomposition method, the global stiffness matrix or the soil flexibility matrix is decomposed in to a Lower unit triangular and an Upper triangular matrix before solution or inversion (29). In the LU version of the program LPG, a symmetry option is included to optimize on the size of the pile group problem using symmetry of pile group geometry. Often a pile group in real world is designed as a square or rectangular array of uniformly spaced piles. This array of piles can be modeled by only a few piles if symmetry of the array is utilized. For example consider the two-pile group shown in Figure 3.13. Assume that both the piles are of equal length and material properties and the top of each pile is subjected to a force of equal magnitude in X direction. Each pile is discretized into four elements and there are five nodes in each pile. There are ten translations in X direction, one translation (degree of freedom) per node. This two-pile group can be modeled by a single pile with five degrees of freedom as explained below. Each displacement at the ten

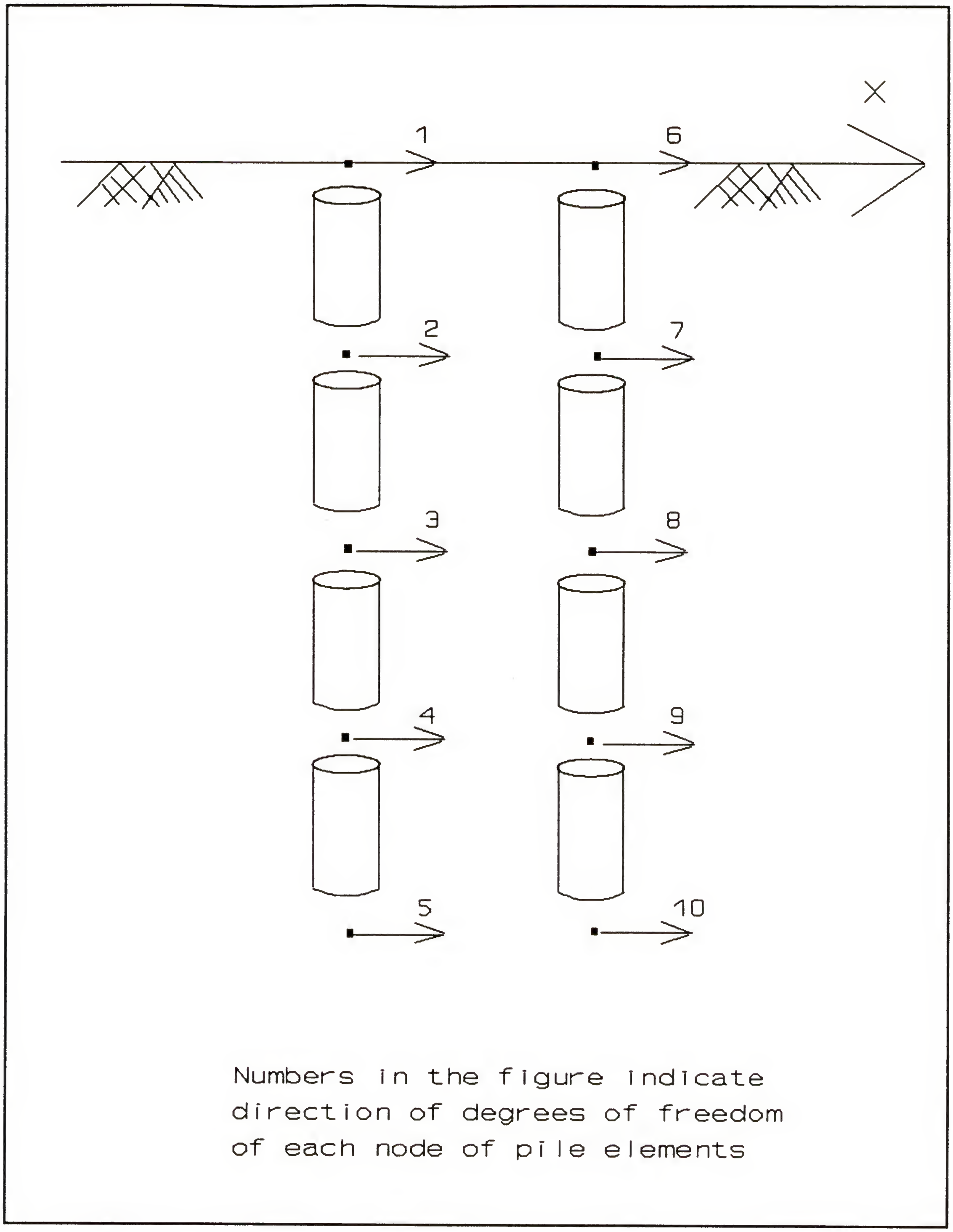


Figure 3.13 Symmetry of Piles in a Two-Pile group.

degrees of freedom of the two-pile group, is solved by the following relationship:

$$\delta_i = \sum_{j=1}^{10} f_{i,j} * q_j \text{ , for } i = 1,10 \qquad \text{... Eqn. 3.16}$$

where δ_i = displacement at degree of freedom i;

$f_{i,j}$ = flexibility of degree of freedom i due to unit force in X direction at degree of freedom j (This flexibility term is obtained after assembling the Mindlin's pile-soil-pile flexibility matrix and the pile-soil flexibility matrix from p-y curves);

q_j = force in X direction at degree of freedom j.

Since both the piles in the two-pile group are geometrically similar and also loaded symmetrically, they will deform identically. So the displacements and forces in X direction at the degrees of freedom one to five of the first pile will be similar to those respectively at degrees of freedom six to ten of the second pile of the two-pile group. Hence the displacements at the degrees of freedom one to five of the two-pile group can be written as:

$$\delta_i = \sum_{j=1}^{10} f_{i,j} * q_j \text{ , for } i = 1,5$$

$$= \sum_{j=1}^{5} (f_{i,j}+f_{i,j+5}) * q_j \text{ , for } i = 1,5 \qquad \text{... Eqn. 3.17}$$

There are 10 unknowns (10 displacements) in equation 3.16 and only 5 unknowns (5 displacements) in equation 3.17. Thus it can be observed that the symmetry of pile group geometry has reduced the problem size. In Appendix G, a

four-pile group problem is reduced to a single pile problem and solved as explained above.

3.6 Program Input and Output

Input format for both versions of the program LPG is given in user's manual of the program (Appendix B). Typical input and output data sets for both versions of the program are included in Appendices F and G.

CHAPTER 4
VERIFICATION

4.1 Introduction

The major objectives of this research are to create a computer program that would calculate the lateral load deformation response of pile groups and to prove that the methods employed were accurate. To verify that the group program works is to compare its results with published linear solutions and also use a commercially available software and compare its results with the group program. The group program is also verified by modelling one of the few full scale lateral load field test.

In order to depict linear soils, two more types of linear p-y curves, in addition to the nonlinear p-y curves for cohesionless and cohesive soils (Section 3.2), were created and they are included as options in the input data format for the program LPG (Appendix B). In one type of linear p-y curve, the secant soil modulus of reaction $Es^{*\dagger}$ (lb/in^2 or N/m^2) defined in equation 4.1, is assumed constant with depth.

---

†Note. The secant modulus of soil reaction Es^* (also commonly denoted as K in literature) is different from Young's modulus of soil Es (18). While soil stiffness is represented by Es in the elastic continuum model, it is represented by Es^* in the subgrade reaction model of the soil behavior.

$Es^* = p/y$ ... Eqn. 4.1

where p = soil reaction (lb/in or N/m);

y = lateral pile deflection (in or m).

In the other type of linear p-y curve Es^* is assumed linearly varying with depth, as given by the following equation:

$Es^* = k\ z$ ... Eqn. 4.2

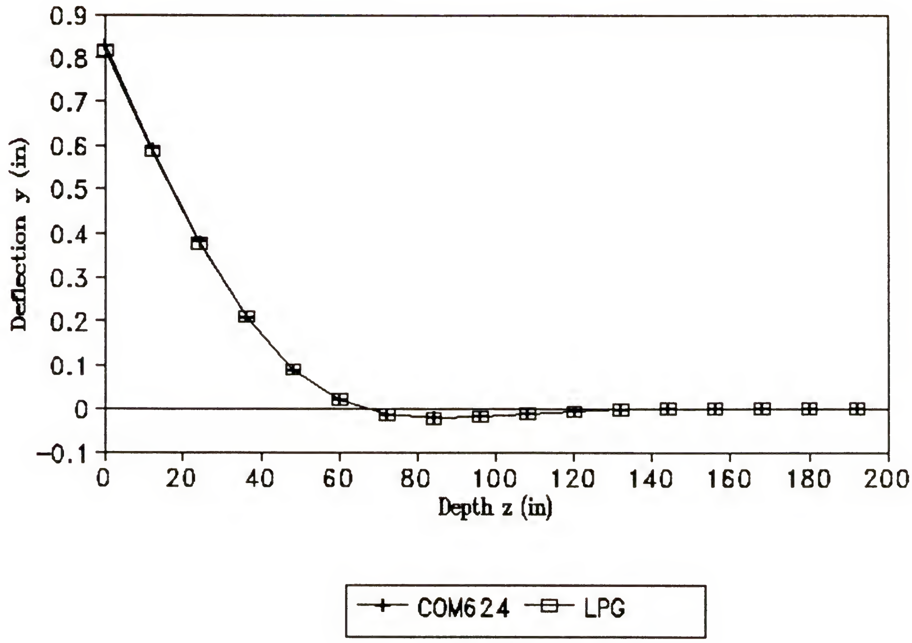
where k = modulus of lateral subgrade reaction (lb/in^3 or N/m^3);

z = depth below ground surface (in or m).

4.2 Single Pile Behavior

Behavior of single piles under lateral load, both for linear and non-linear elastic soils, was verified by the program COM624 (23), a commercially available software. For linear elastic soil, a linear soil modulus Es^* linearly varying with depth was assumed. For non-linear elastic soil, the p-y curve suggested by O'Neill for cohesionless soil (Section 3.2.1) is used.

Figures 4.1 (a)-(c) show the results of free headed single piles. From the results, one will observe that the program LPG predicts lateral deflection and bending moment distribution along the pile length very well for linear elastic soil. Also one will notice that the lateral pile-head load-deflection for non-linear soil, predicted by both the programs LPG and COM624 agree very well.



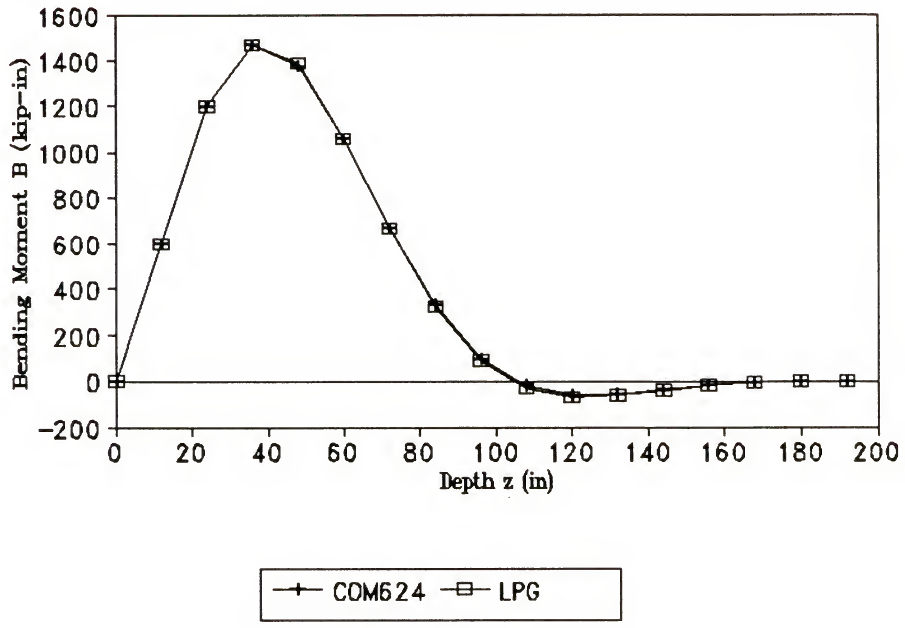
Given:

L=192"; D=12"; $E=4x10^6$ psi; Z=12"; $I=1018\ in^4$; $A=113\ in^2$; k=500 pci; Ht=50 kip; # of Finite Elements=16.

Description:

L = Length of pile;
D = Diameter of pile;
E = Young's modulus of pile material;
Z = Free standing height of pile above ground surface;
I = Moment of inertia of pile cross section;
A = Area of cross section of pile;
k = Modulus of horizontal subgrade reaction for linear elastic soil springs (pci);
  = p/(y*z);
p = Soil reaction (lb/in) at any depth z (in) in soil;
y = Horizontal deflection of pile at the depth z;
Ht = Horizontal load applied at top of pile.

Figure 4.1. Results of Free Headed Single Pile Comparison with COM624 Solution.
(a) Deflection Vs Depth for Linear p-y Curve;



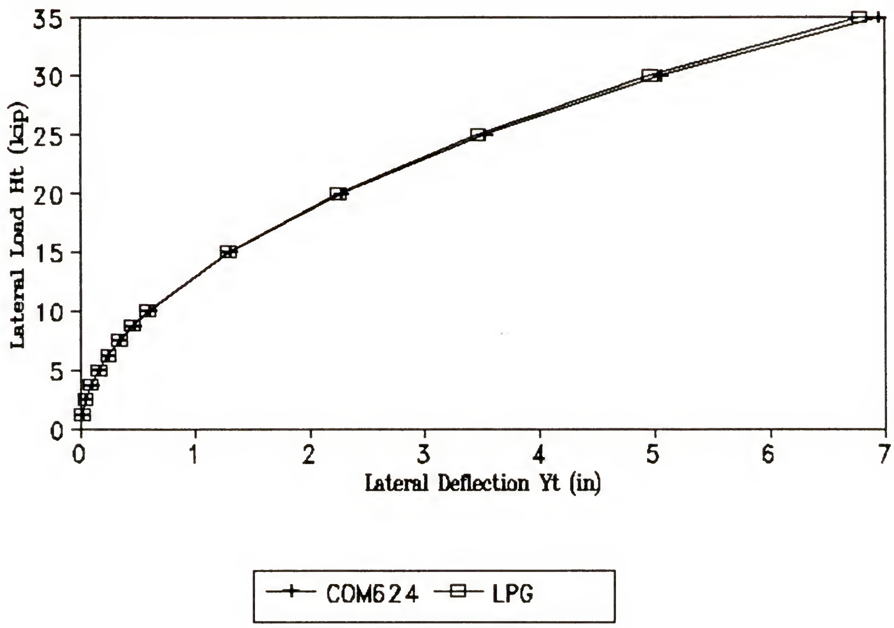
Given:

Same parameters as in Figure 4.1.(a).

Description:

Same as in Figure 4.1.(a).

Figure 4.1.--Continued.
(b) Bending Moment Vs Depth for Linear p-y Curve;



Given:

L=192"; D=12"; E=$4x10^6$ psi; Z=12"; I=1018 in^4; A=113 in^2; ϕ=25°; k=500 pci; γ'=110 pcf; # of Finite Elements=16.

Description:

k = Modulus of horizontal subgrade reaction for non-linear elastic springs suggested by O'Neill (14) for cohesionless soils;
ϕ = Angle of internal friction of the soil;
γ' = Effective unit weight of the soil;
Yt = Horizontal deflection at top of the single pile

Description of all other parameters remain the same as in Figure 4.1.(a).

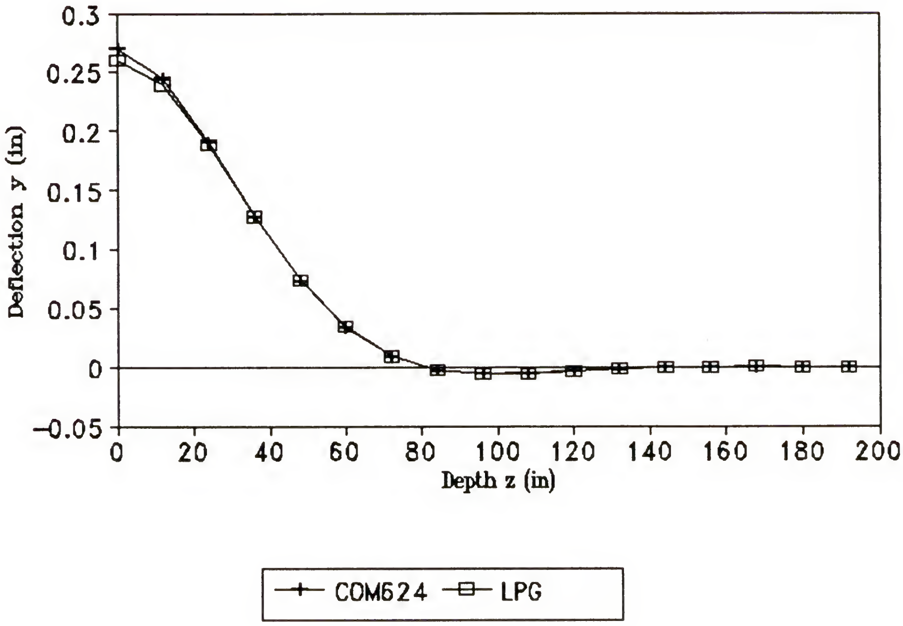
Figure 4.1.--Continued.
(c) Pile-Head Load Vs Deflection for Non-Linear p-y Curve.

Figures 4.2 (a)-(c) present the results for fixed headed single piles. The results, like those for free headed case, show that the program LPG predicts similar to COM624.

4.3 Pile Group Behavior

4.3.1 Linear elastic soil

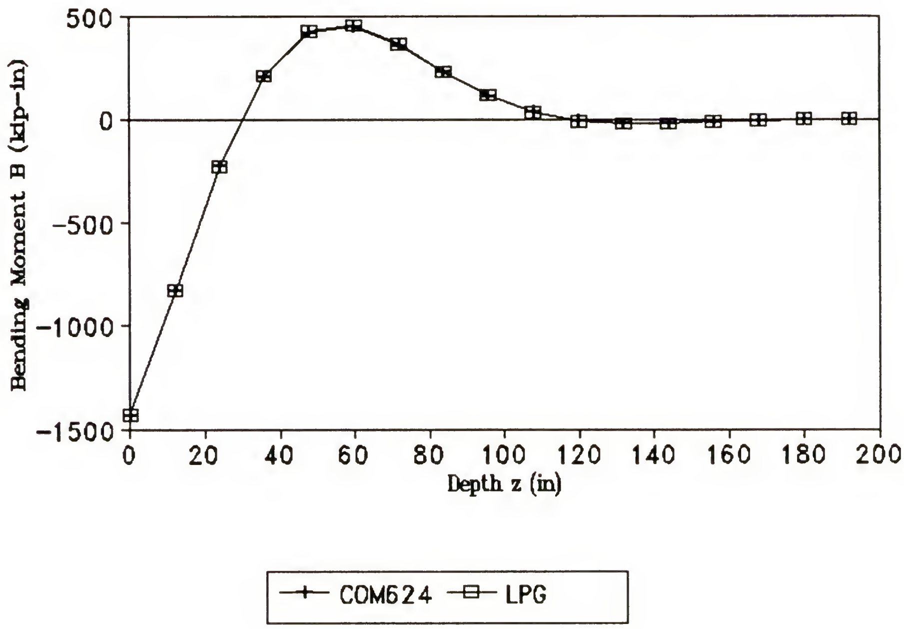
Pile group behavior, under lateral loads, for linear elastic soils was verified with Polous's published results (17,18). The Poulos's work assumes the soil to be a homogeneous elastic continuum where as the program LPG models the soil by discrete linear or nonlinear soil springs. So the numerical value of the Young's modulus Es for a linear elastic soil represented by Poulos's elastic continuum model and the soil modulus Es^* for the linear elastic soil represented by the program LPG's linear p-y springs model will not be the same. Consequently, in order to compare the results of both the models, a linear soil modulus Es^* constant with depth was selected such that response of a laterally loaded single pile predicted by LPG is similar to that from a finite element solution. The finite element solution used herein for this purpose is the one given by Randolph (20) which also assumes the soil to be a homogeneous elastic continuum. Also the finite element solution for the single pile is simpler than the Poulos's solution and it predicts similar to the latter.



Given:
Same parameters as in Figure 4.1.(a).

Description:
Same as in Figure 4.1.(a).

Figure 4.2. Results of Fixed Headed Single Pile Comparison with COM624 Solution.
(a) Deflection Vs Depth for Linear p-y Curve;



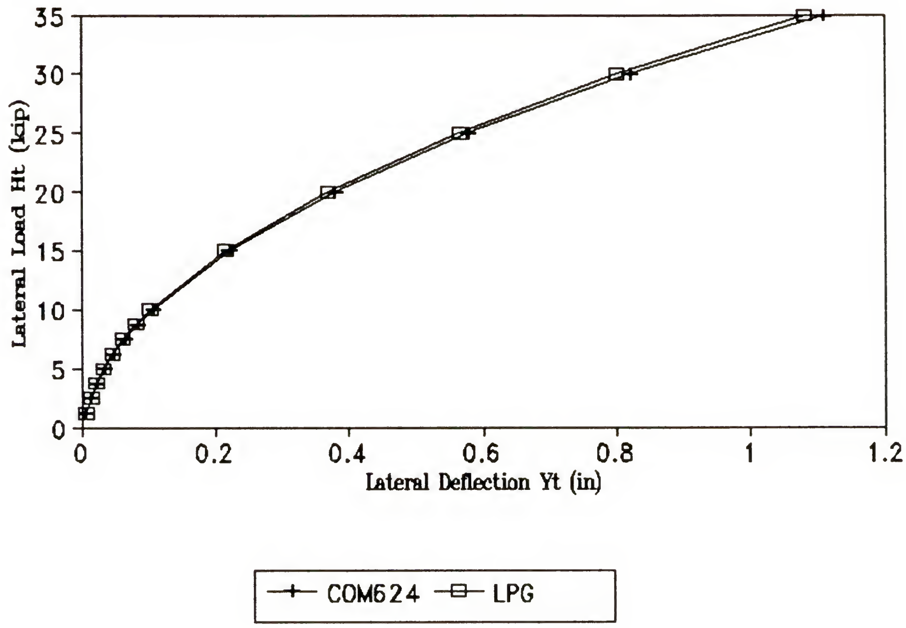
Given:

Same parameters as in Figure 4.1.(a).

Description:

Same as in Figure 4.1.(a).

Figure 4.2.--Continued.
(b) Bending Moment Vs Depth for Linear p-y Curve;



Given:

$L=192"$; $D=12"$; $E=4x10^6$ psi; $Z=12"$; $I=1018$ in^4; $A=113$ in^2; $\phi=25^{\circ}$; $k=500$ pci; $\gamma'=110$ pcf; # of Finite Elements=16.

Description:

k = Modulus of horizontal subgrade reaction for non-linear elastic springs suggested by O'Neill (14) for cohesionless soils;
ϕ = Angle of internal friction of the soil;
γ' = Effective unit weight of the soil;
Yt = Horizontal deflection at top of the single pile

Description of all other parameters remain the same as in Figure 4.1.(a).

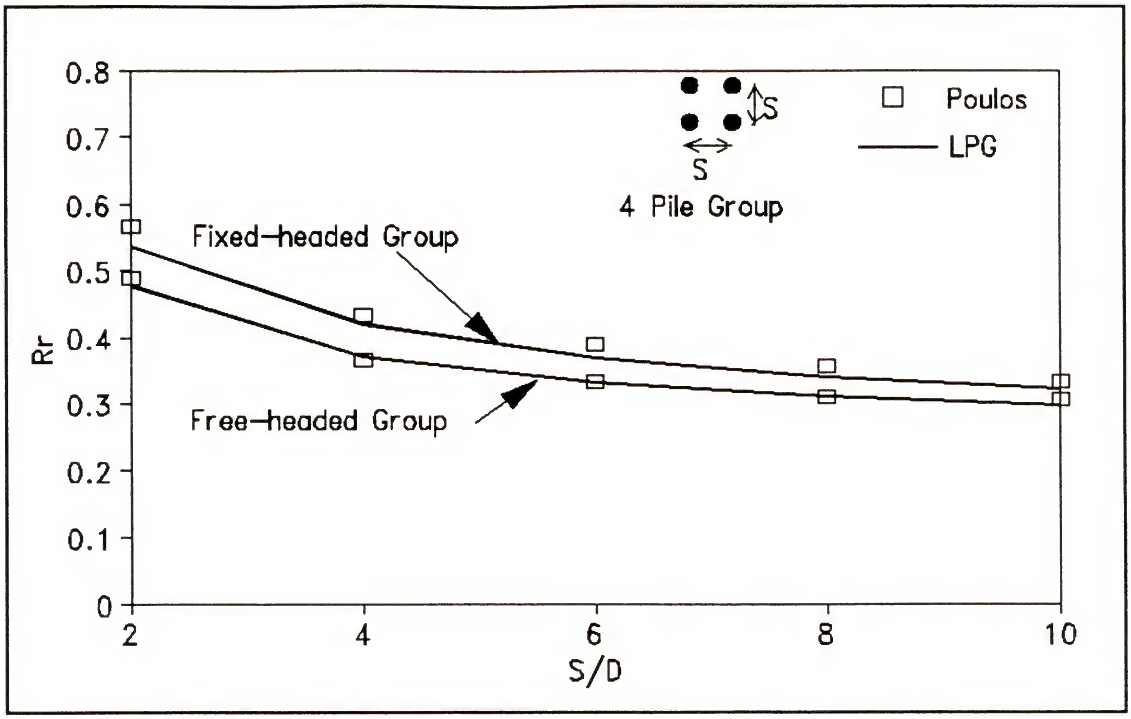
Figure 4.2.--Continued.
(c) Pile-Head Load Vs Deflection for Non-Linear p-y Curve.

Figures 4.3 (a)-(b) present the results for four pile group in an elastic soil. From the results one will observe that the program LPG predicts well for both fixed and free pile-heads. Also one will observe that it predicts lower group displacements compared to Poulos's results when l/d ratio is larger.

Figures 4.4 (a)-(d) show the results for a sixteen pile group in an elastic soil. From the results one will observe that the program LPG, when compared to the Poulos's results, predicts:

1. equally well for both fixed and free headed piles;
2. lower and comparable group displacement ratios for higher and lower l/d ratios respectively;
3. comparable and not comparable horizontal load distribution for lower and higher l/d ratios respectively.

The larger discrepancy for the higher l/d ratio (or longer piles), as observed in the Figures 4.3 (a)-(b) and 4.4 (a)-(d), may be due to difference in modeling of the soil and solution technique used. As mentioned elsewhere, a continuum model and discrete elements model are used respectively in the Poulos's work and the program LPG to represent the soil. The solution technique used in the Poulos's work is Integral Equation Method where as in the program LPG, it is Finite Element Method.



Given:

$L/D=25$; $\mu_s=0.5$; $Kr=10^{-5}$.

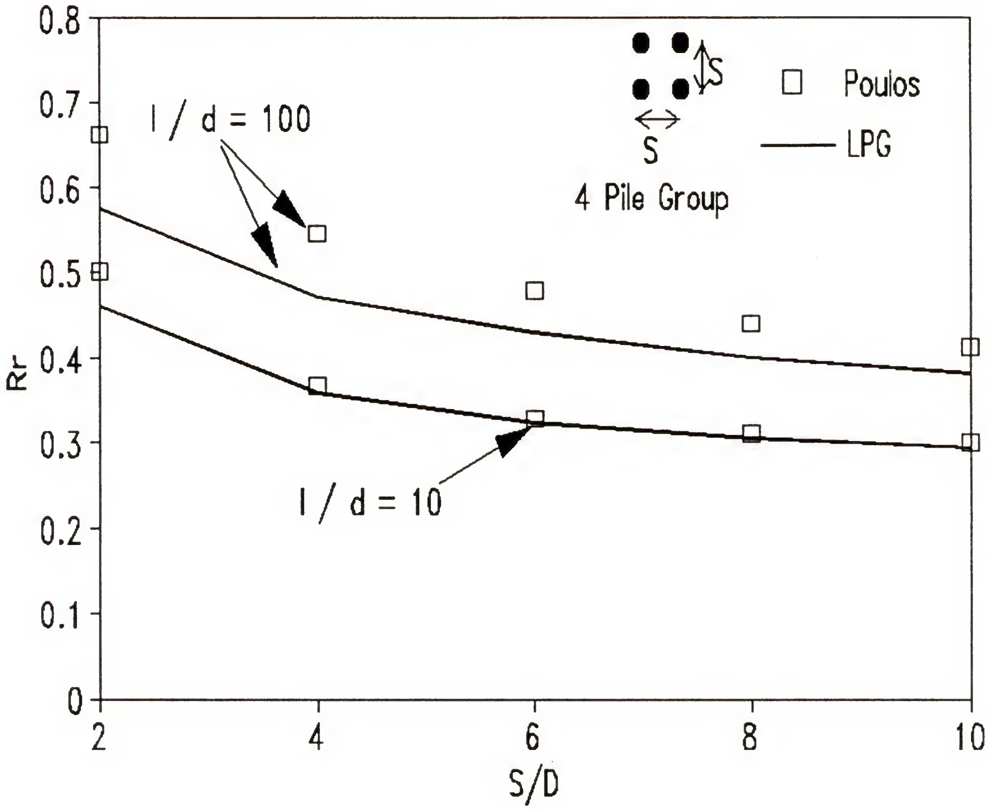
Description:

H_g = Total load applied to all piles in a group;
Es = Young's modulus of elastic half space material;
D = Diameter of each pile in the group;
y_g = Lateral displacement of the top of each pile in the group (Equal displacement at all pile heads);
y_u = Lateral displacement of the top of a single pile carrying a unit load;
S = Center to center spacing of piles in the group;
μ_s = Poisson's ratio of the elastic half space material;
L = Length of each pile in the group;
Ip = Moment of inertia of pile cross section;
Ep = Young's modulus of pile material;
Rr = Ratio of the group displacement to the displacement of a single pile carrying the same total load as the group;

$$= \frac{y_g}{H_g\ y_u} \ ;$$

$$Kr = \frac{EpIp}{EsL^4} \ .$$

Figure 4.3. Results of Four-Pile Group Comparison with Poulos's Elastic Solution.
(a) Influence of Pile-head fixity on Rr;



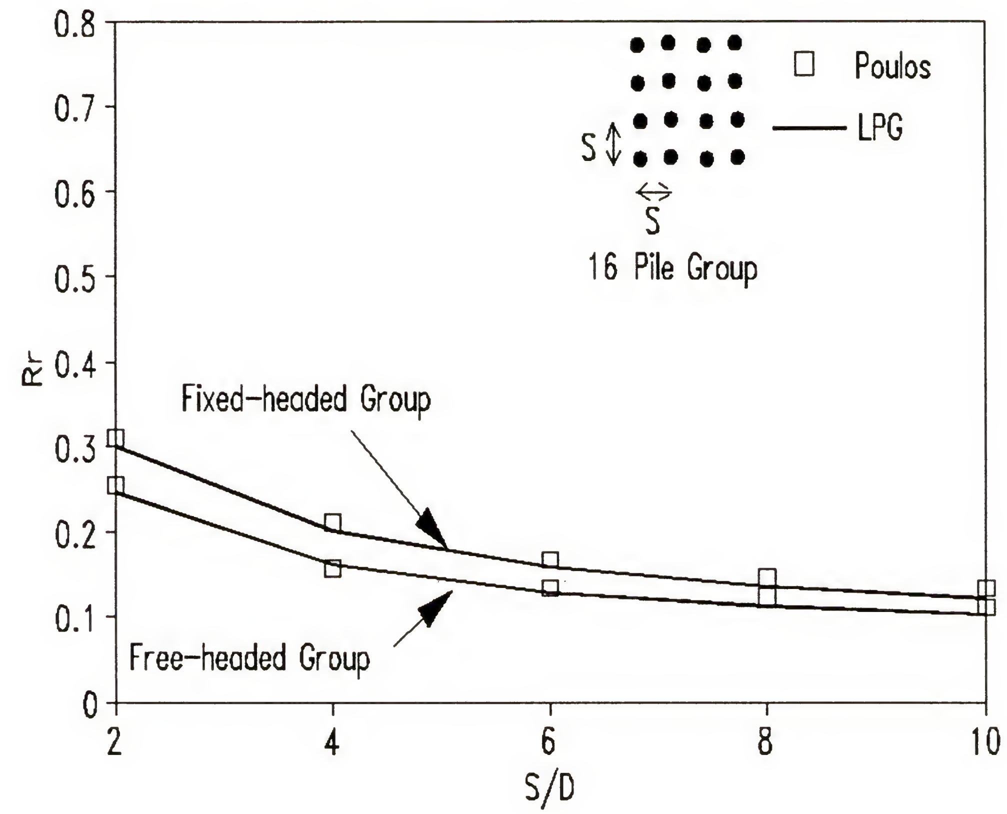
Given:

$Kr=10^{-5}$; $\mu_s=0.5$; Fixed-headed group.

Description:

Same as in Figure 4.3.(a).

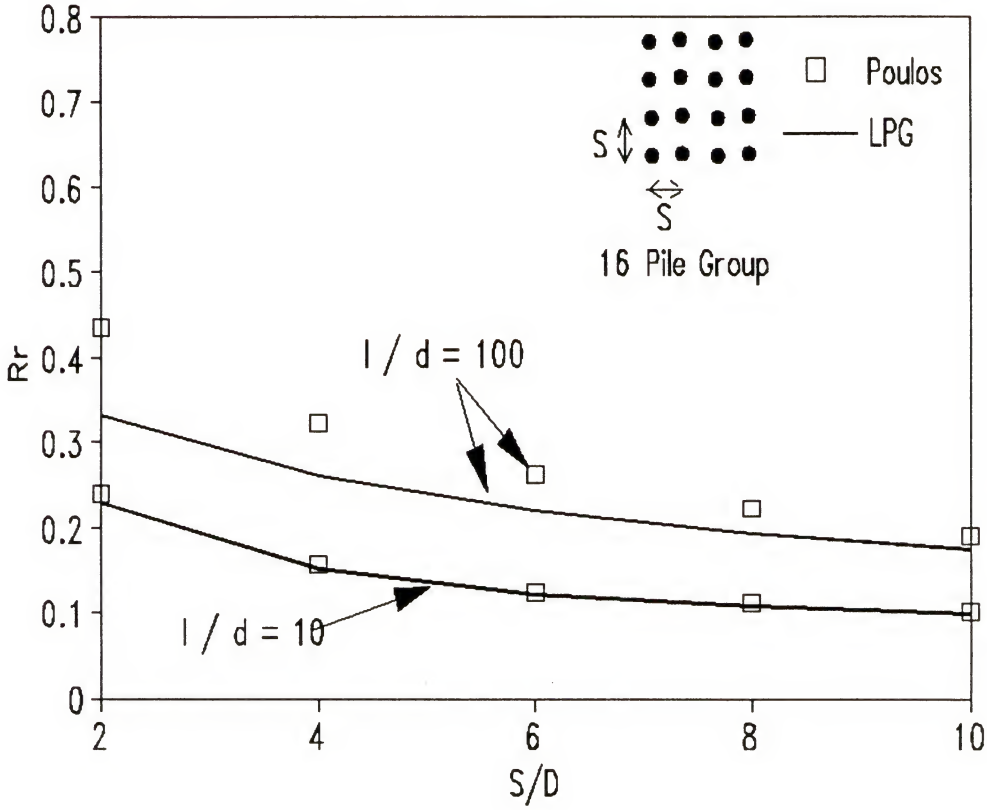
Figure 4.3--Continued.
(b) Influence of L/D on Rr.



Given:
    L/D=25; μ_s=0.5;   Kr=10^{-5}.

Description:
    Same as in Figure 4.3.(a).

Figure 4.4. Results of Sixteen-Pile Group Comparison with Poulos's Elastic Solution.
(a) Influence of Pile-Head Fixity on Rr;



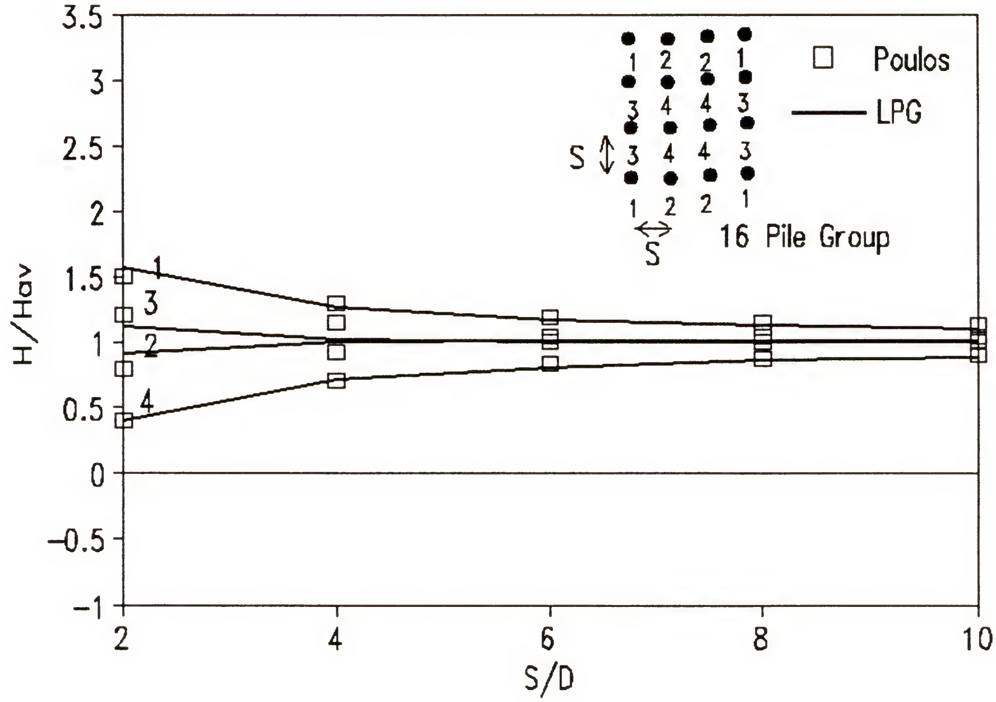
Given:

Kr=10^{-5}; μ_s=0.5;   Fixed-headed group.

Description:

Same as in Figure 4.3.(a).

Figure 4.4.--Continued.
(b) Influence of L/D on Rr;



Given:

Kr=10^{-5}; μ_s=0.5.

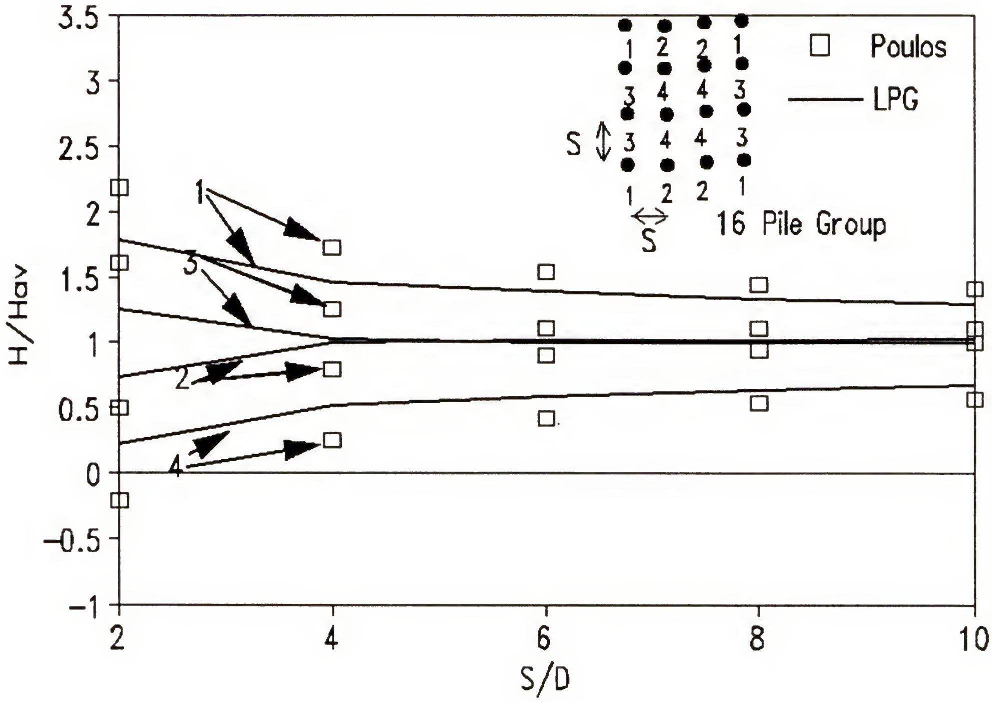
Description:

H = Horizontal load on a pile in a group;

Hav = Average of horizontal loads on all piles in the group.

Description of all other parameters are the same as in Figure 4.3.(a).

Figure 4.4--Continued.
(c) Horizontal Load Distribution for Fixed Pile-Heads and L/D = 10;



Given:

Kr=10^{-5}; μ_s=0.5.

Description:

H = Horizontal load on a pile in a group;

Hav = Average of horizontal loads on all piles in the group.

Description of all other parameters are the same as in Figure 4.3.(a).

Figure 4.4--Continued.
(d) Horizontal Load Distribution for Fixed Pile-Heads and L/D = 100;

4.3.2 Nonlinear Elastic Soil

Regarding verification of pile group response predicted by the program LPG, for a nonlinear or a realistic soil, the data obtained from a field load test are used and the results are discussed in next section.

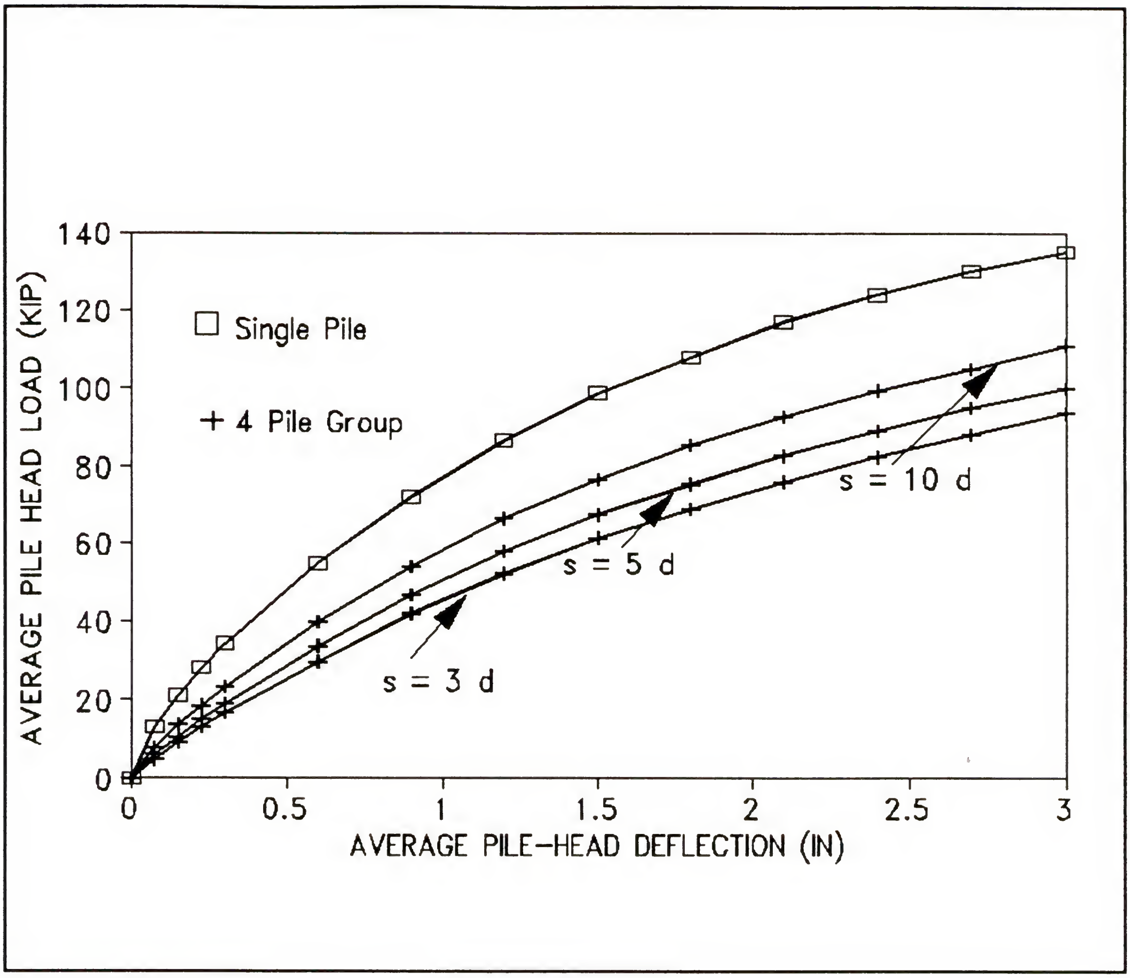
Before going to next section, typical load deflection responses for static loading predicted by the program LPG for a four-pile group and a single pile for a typical realistic nonlinear soil profile, are depicted in figure 4.5. Input and output for this analysis are given in Appendix G. The soil data, used for both the single pile and four-pile group, might be representative of a stiff clay. From the figure 4.5, following conclusions can be drawn:

1. because the load transfer curves are nonlinear in nature, both the single and the group response are nonlinear;

2. a single pile carries the maximum pile-head load for a particular pile-head lateral deflection when compared to the average load carried by a group pile for the same pile-head lateral deflection;

3. when the spacing between the group piles increases, the group piles tend to behave like a single pile.

It was also found from further analysis that the group response for the four-pile group shown in figure 4.5 significantly depends on shear modulus Gs of the soil



Given:

$L=540''$; $E=10\text{x}10^6$ psi; $I=2898$ in^4; $A=86$ in^2; $D=18''$; $Z=54''$; Static loading; $\mu=0.5$; Fixed-headed group; $G_s=600$ psi; $Cu=18$ psi; $\epsilon_{50}=0.005$; $\epsilon_{100}=0.01$.

Description:

Gs = average shear modulus of soil along the length of pile;
μ = Poisson's ratio of soil;
Cu = undrained shear strength of soil;
ϵ_{50} = UU triaxial compression strain at 50% of failure deviatoric stress of soil;
ϵ_{100} = UU triaxial compression failure strain of soil.

Description of all other parameters are the same as in Figure 4.1.(a).

Figure 4.5. Typical Non-Linear Behavior of a Single Pile and Four-Pile Group as Predicted by LPG.

separating the piles. Typical load-deflection response for cyclic loading, both for the single pile and four-pile group, will also be similar to the static loading case depicted in figure 4.5.

4.4 Houston, Texas Pile Group Study

After a thorough literature review, it was found that only data from a single field load test, for a lateral loaded pile group, with individual pile-head load-deflection and pile-head load-maximum bending moment measurements, are available to study for this dissertation. The load test data available are the results obtained from a field static and cyclic lateral load test on a single and nine-pile group in Houston, Texas in December 1984 (3). Both the single pile and the piles in the group were 10.75 inch outer diameter and the group piles were at a spacing of three times the outer diameter. The soil profile of the load test site consisted of an artificially compacted dense sand overlying a natural clay deposit. The ground water table was at the ground surface level. Figures 4.6 and 4.7 depict the schematic drawing of the single pile and group piles used for the load test program at Houston, Texas. Included also in the figures is the soil profile at the load test site. In order to model any single pile or pile group with the program LPG, the following engineering characteristics of the soil are needed:

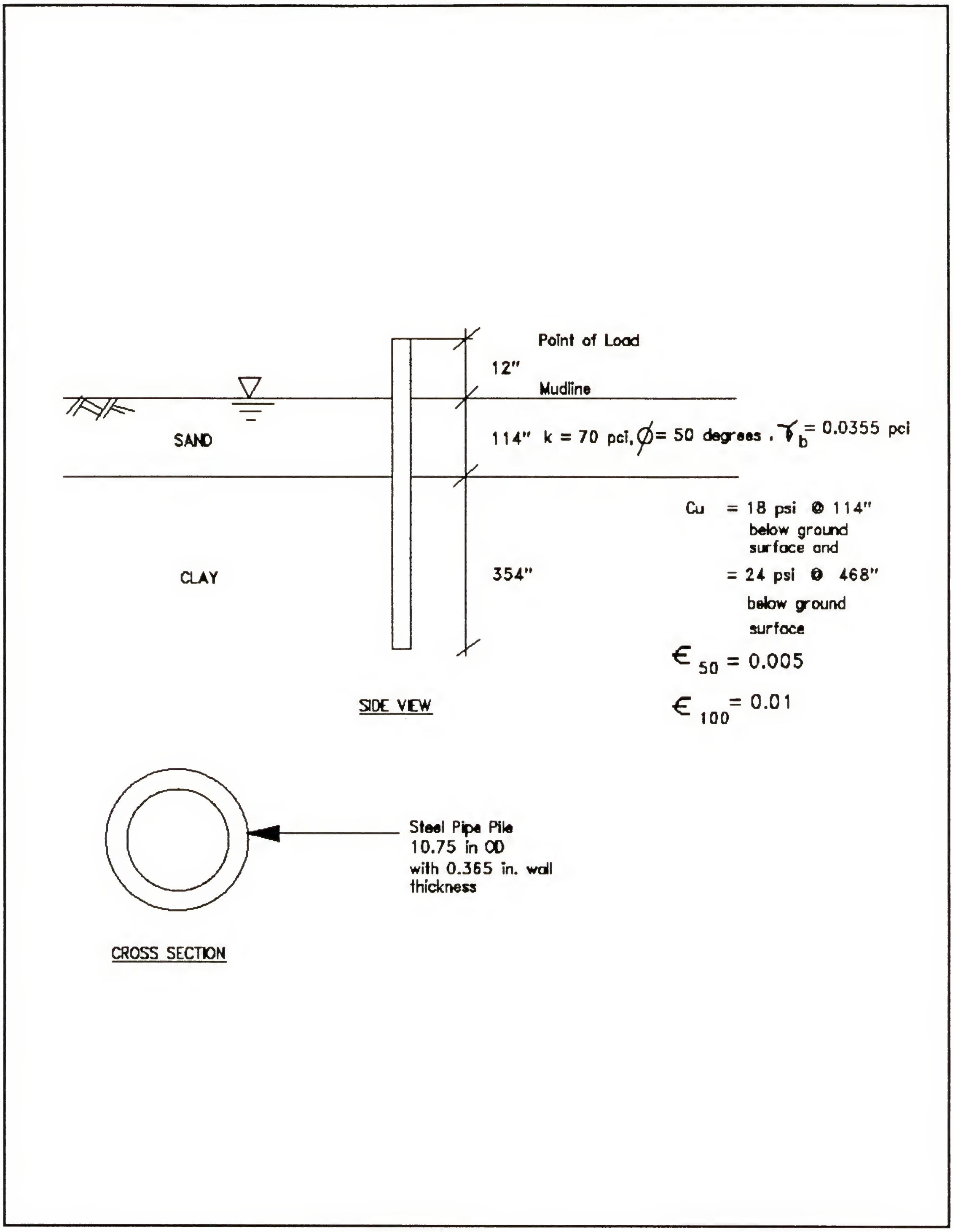


Figure 4.6. Schematic Drawing of Single Pile, Houston, Texas.

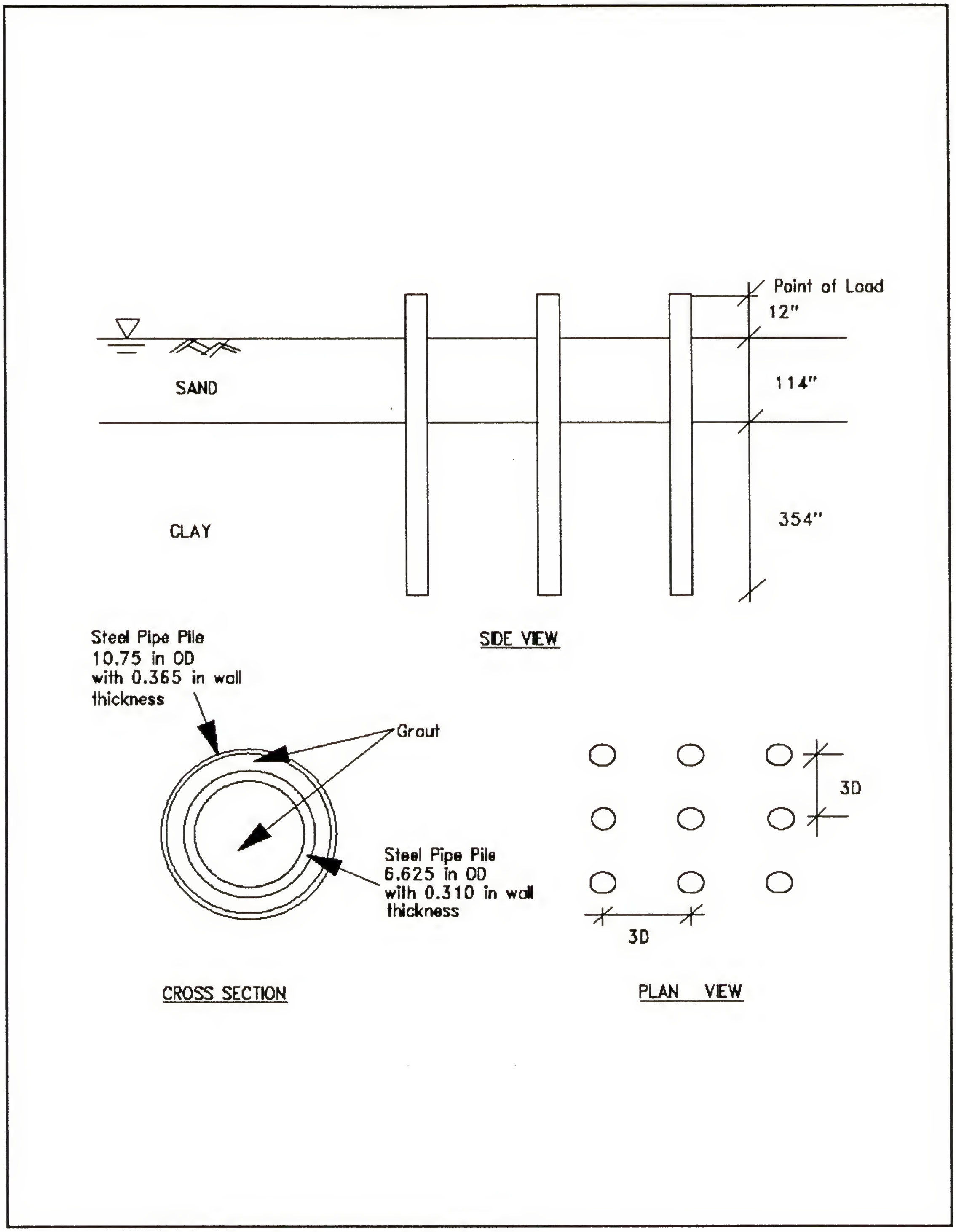


Figure 4.7. Schematic Drawing of Pile Group, Houston, Texas.

Gs, μ ≡ parameters to calculate Mindlin's pile-soil-pile interaction (Section 3.3);

K_z ≡ parameter to define linear force-displacement relationship for soil at pile tip;

ϕ, k, γ ≡ parameters to define non-linear p-y curve for sand (Section 3.2.1);

Cu, ϵ_{50}, ϵ_{100} ≡ parameters to define non-linear p-y curve for clay (Section 3.2.2);

where

Gs = average shear modulus of soil (lb/in^2 or N/m^2) along the length of pile;

μ = Poisson's ratio of soil;

K_z = axial linear tip spring stiffness (lb/in or N/m).

ϕ = angle of internal friction of soil (degree);

k = modulus of horizontal subgrade reaction of soil (lb/in^3 or N/m^3);

γ = effective unit weight of soil (lb/in^3 or N/m^3);

Cu = undrained shear strength of soil;

ϵ_{50} = UU triaxial compression strain at 50% of failure deviatoric stress of soil;

ϵ_{100} = UU triaxial compression failure strain of soil.

Regarding the appropriate shear modulus of the soil Gs to be used in the Mindlin's pile-soil-pile interaction calculations, there is not sufficient data in the literature

and research like centrifuge model testing needs to done. Until more information is available, the shear modulus of the soil Gs may be calculated from the Young's modulus Es and the Poisson's ratio μ of the soil, using the following elasticity equation:

$$Gs = \frac{Es}{2\ (1+\mu)} \qquad \text{... Eqn. 4.3}$$

For a cohesionless soil, the Young's modulus Es is obtained from its modulus of lateral reaction k (lb/in^3 or N/m^3) as given by the equation 3.6. For a cohesive soil, the Young's modulus Es is obtained from its correlation to undrained shear strength Cu as given by O'Neill (6) in Table 3.2 or Banerjee and Davies (1) in equation 3.5. Table 4.1 summarizes the calculations for the average shear modulus Gs used for analysis in the Houston, Texas single pile and group piles study. For Poisson's ratio, a typical value of 0.3 for sand and 0.5 for clay (18) is used. From the Table 4.1, it can be observed that two different numerical values, 564 and 842 psi are available for Gs. The differences in the values are due to two different correlations, one suggested by O'Neill (6) and the other by Banerjee and Davies (1), used for evaluating Es for clay. For clarity, analyses by the program LPG using Gs equal to 564 and 842 psi will be called LPG-O'Neill and LPG-Banerjee respectively henceforth. It is noted that for clay, the same Es-Cu correlation for evaluating Es, is also used for calculating its non-linear p-y curve (Section 3.2.2).

Table 4.1. Calculation of Shear Modulus Gs for Soil Profile at the Houston Pile Group Load Test Site.

NODE # (1)	Z (IN) (2)	Cu (PSI) (3)	k (PCI) (4)	μ (5)	Es^a (PSI) (6)	Es^b (PSI) (7)	Gs^c (PSI) (8)	Gs^d (PSI) (9)	SOIL (10)
1	0.5	—	—	—	—	—	—	—	—
2	12.0	—	70	0.3	0.0	0.0	0.0	0.0	SAND
3	43.2	—	70	0.3	2184.0	2184.0	840.0	840.0	SAND
4	74.4	—	70	0.3	4368.0	4368.0	1680.0	1680.0	SAND
5	105.6	—	70	0.3	6552.0	6552.0	2420.0	2520.0	SAND
6	136.8	18.183	—	0.5	774.6	1818.3	258.2	606.1	CLAY
7	168.0	18.712	—	0.5	814.6	1871.2	271.5	623.7	CLAY
8	199.2	19.241	—	0.5	894.6	1924.1	284.9	641.4	CLAY
9	230.4	19.770	—	0.5	894.6	1977.0	298.2	659.0	CLAY
10	261.6	20.298	—	0.5	934.6	2029.8	311.5	676.6	CLAY
11	292.8	20.827	—	0.5	974.5	2082.7	324.8	694.2	CLAY
12	324.0	21.356	—	0.5	1014.5	2135.6	338.2	711.9	CLAY
13	355.2	21.885	—	0.5	1054.5	2188.5	351.5	729.5	CLAY
14	386.4	22.414	—	0.5	1094.5	2241.4	364.8	747.1	CLAY

Table 4.1. -- Continued.

NODE # (1)	Z (IN) (2)	Cu (PSI) (3)	k (PCI) (4)	μ (5)	Es[a] (PSI) (6)	Es[b] (PSI) (7)	Gs[c] (PSI) (8)	Gs[d] (PSI) (9)	SOIL (10)
15	417.6	22.942	—	0.5	1134.4	2294.2	378.1	764.7	CLAY
16	448.8	23.471	—	0.5	1174.4	2347.1	391.5	782.4	CLAY
17	480.0	24.000	—	0.5	1214.4	2400.0	404.8	800.0	CLAY
				AVERAGE = 0.45			AVERAGE = 563.6 PSI	AVERAGE = 842.3 PSI	

NOTES:

a. (6) = [(2)-12.0] * (4) for sand (Polous's correlation given in eqn. 3.6)
   (6) = From Table 3.2 using (3) for clay (O'Neill's correlation);

b. (7) = [(2)-12.0] * (4) for sand (Polous's correlation given in eqn. 3.6)
   (7) = (3) * 100 for clay (Banerjee and Davies correlation given in eqn. 3.5);

c. $(8) = \dfrac{(6)}{2 * [1.0 + (5)]}$; d. $(9) = \dfrac{(7)}{2 * [1.0 + (5)]}$.

Any value can be used for the axial tip spring stiffness K_z (lb/in or N/m) for the field load test being analyzed, since only lateral load behavior is studied in this dissertation. Also the lateral group or single pile behavior is independent of axial behavior for the program LPG since axial pile element stiffnesses are uncoupled from lateral stiffnesses i.e. no P-δ effect (Section 3.1). Consequently a value of 10^{-3} lb/in is used for K_z.

To define p-y curves for sand, an angle of internal friction $\phi^{\dagger}$ equal to 50°, a modulus of subgrade reaction $k^{\dagger}$ equal to 70 pci and an effective unit weight of 0.0355 pci are used.

To define p-y curves for clay, following input values are used for Cu, ϵ_{50} and ϵ_{100}:

Cu = 18 psi at top of clay layer and

= 24 psi at pile tip in clay;

ϵ_{50} = 0.005;

ϵ_{100} = 0.01.

Figure 4.8 depicts definition of leading, middle and trailing rows of the pile group analyzed. For either compression or tension stroke, a leading row is defined as

---

†<u>Note</u>. Actually Brown (3) back figured the input parameters ϕ=50° and k=60 pci by fitting measured p-y data in the p-y curve suggested by Reese et al. (21). Since the program LPG uses the p-y curve suggested by O'Neill (14) which is slightly different from the curve used by Brown (Section 3.2.1), the input parameters ϕ=50° and k=70 pci were selected so that both the curves produced the same p-y relationship.

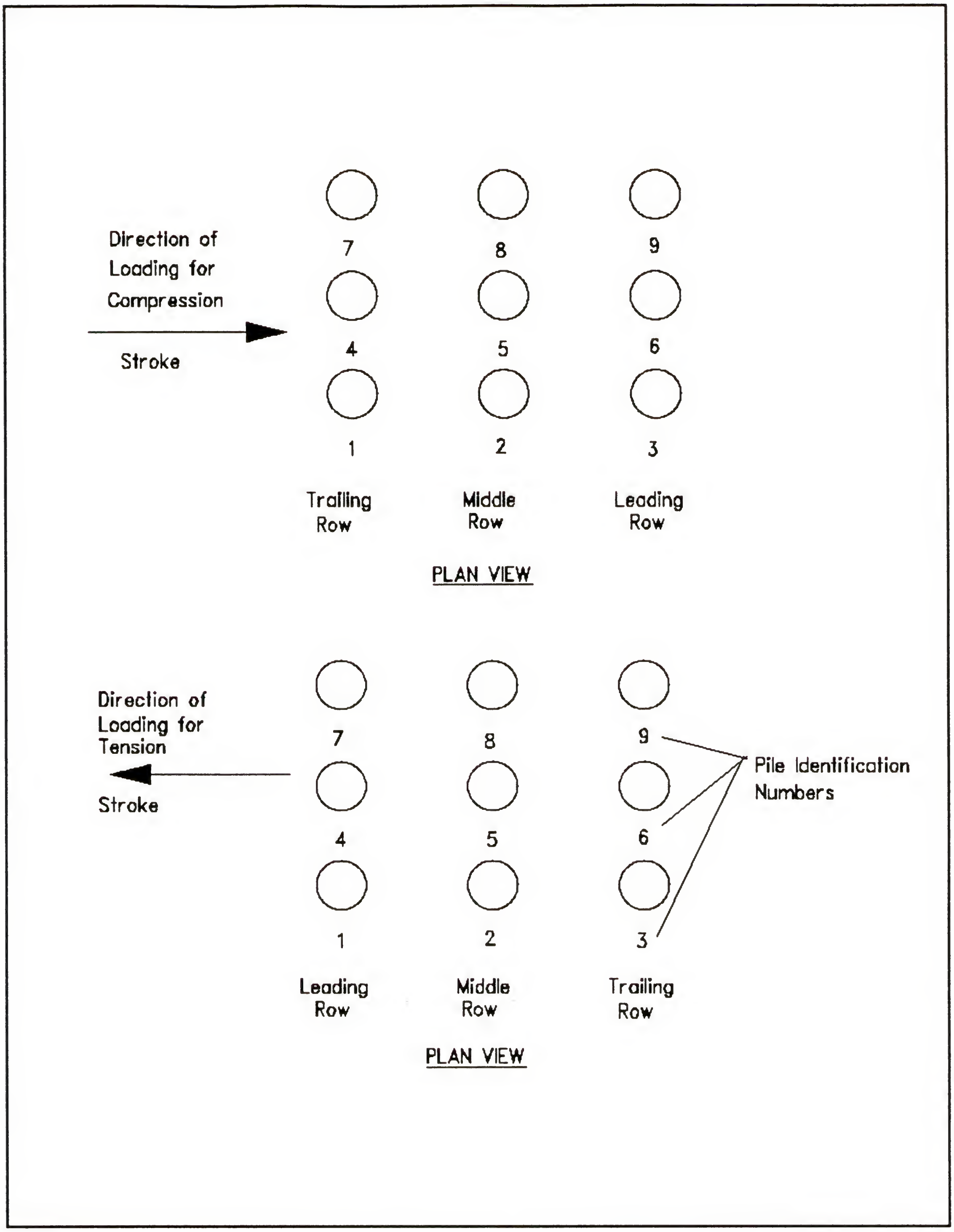


Figure 4.8. Definition of Leading, Middle and Trailing Rows and Pile Identification Numbers for the Houston, Texas Pile Group.

the row which is in contact with virgin soil with out any 'shadow' effects of other rows. The trailing row is the last row in the direction of loading for either compression or tension stroke and the middle row is the row in between the leading and the trailing row.

Response of the single pile and the pile group predicted by the program LPG, in comparison to the field static and cyclic load test data, is discussed below. In predicting the response of the group, field pile-head displacements of each pile in the group are used as prescribed boundary conditions for each load case. Appendix F includes a typical input and output data set of the single pile and nine-pile group analyzed.

4.4.1 Static Loading

Figures 4.9 and 4.10 present pile-head load-deflection and load-maximum bending moment responses of the single pile for cycle #1 predicted by the program LPG. The predicted responses match very well with the field data.

Figures 4.11 (a)-(i) depict pile-head load-deflection response of each pile of the nine-pile group for cycle #1 predicted by the program LPG. From the figures it can be observed that the program LPG, for both O'Neill's and Banerjee's Gs values, over predicted the load for some piles and under predicted for the rest for a particular pile-head deflection. Figures 4.11 (j)-(l) presents the response of leading, middle and trailing rows. It can be interpreted

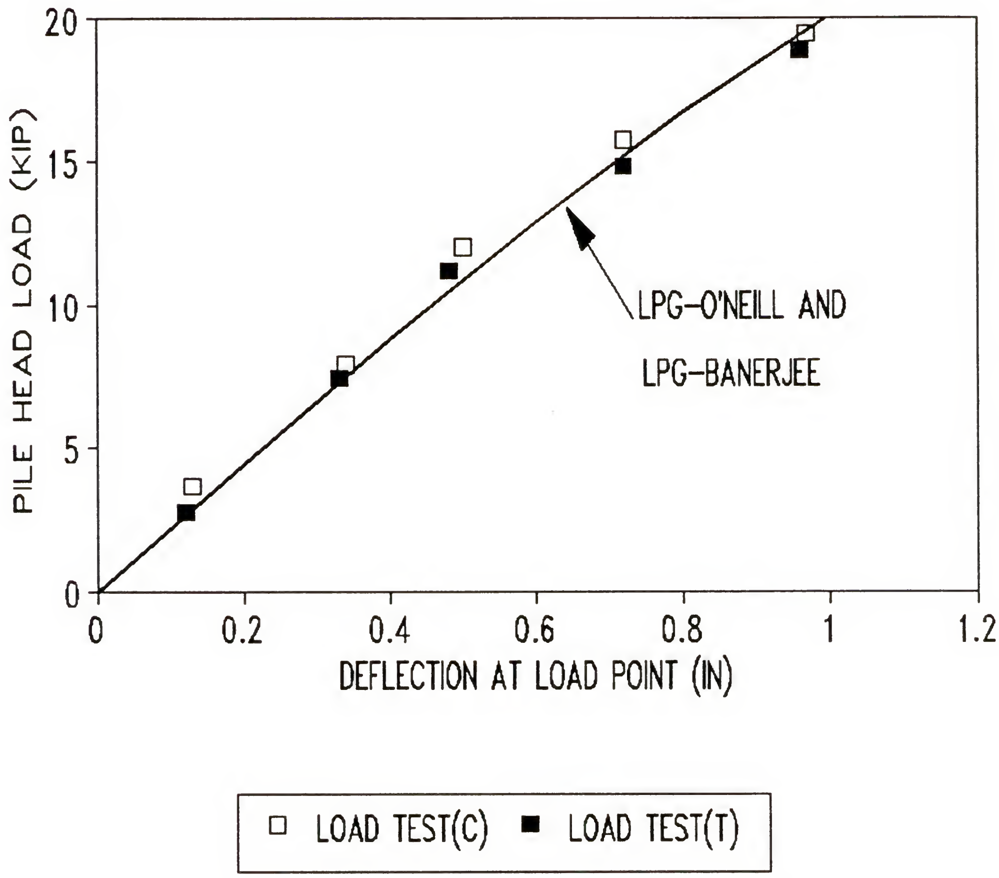


Figure 4.9. Pile-Head Load Vs Deflection for the Houston, Texas Single Pile for Cycle #1.

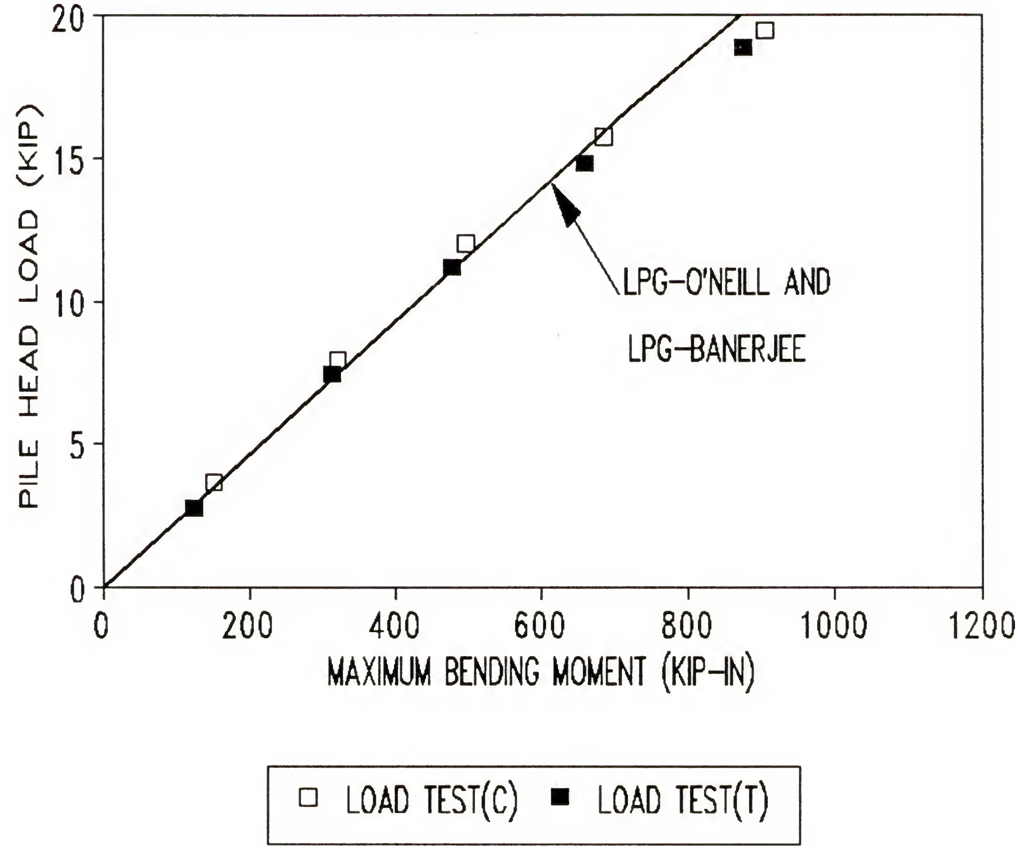


Figure 4.10. Pile-Head Load Vs Maxmimum Bending Moment for the Houston, Texas Single Pile for Cycle #1.

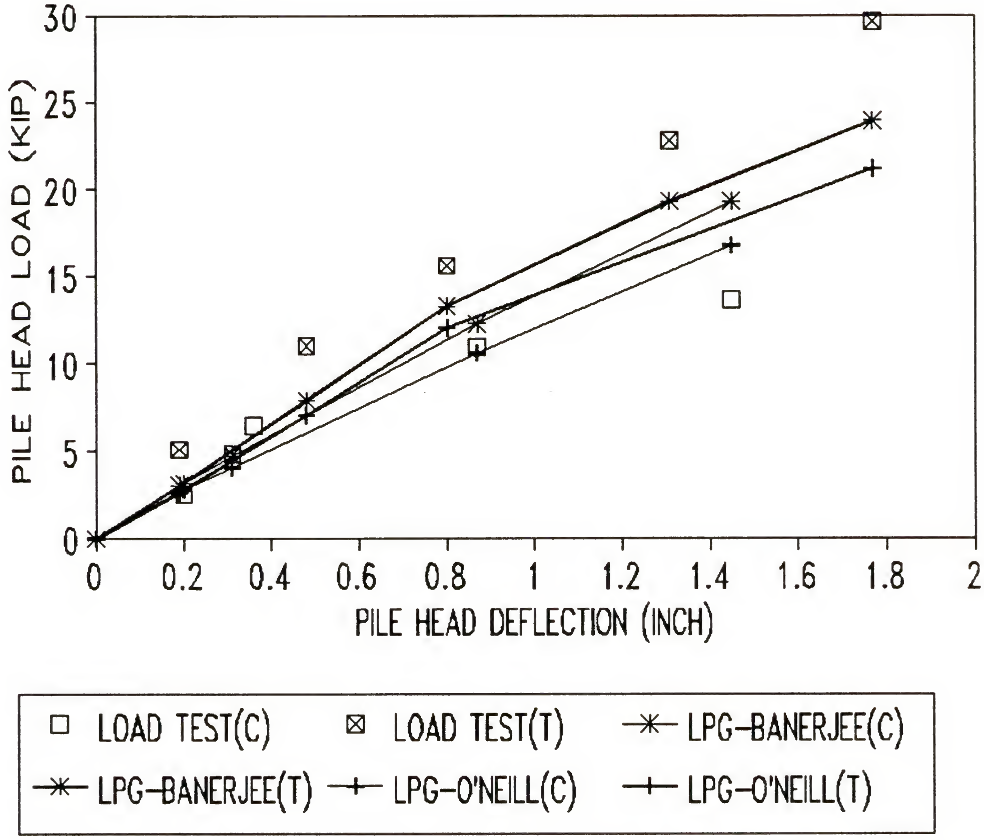


Figure 4.11. Pile-Head Load Vs Deflection for the Houston, Texas Pile Group for Cycle #1.
(a) Pile #1;

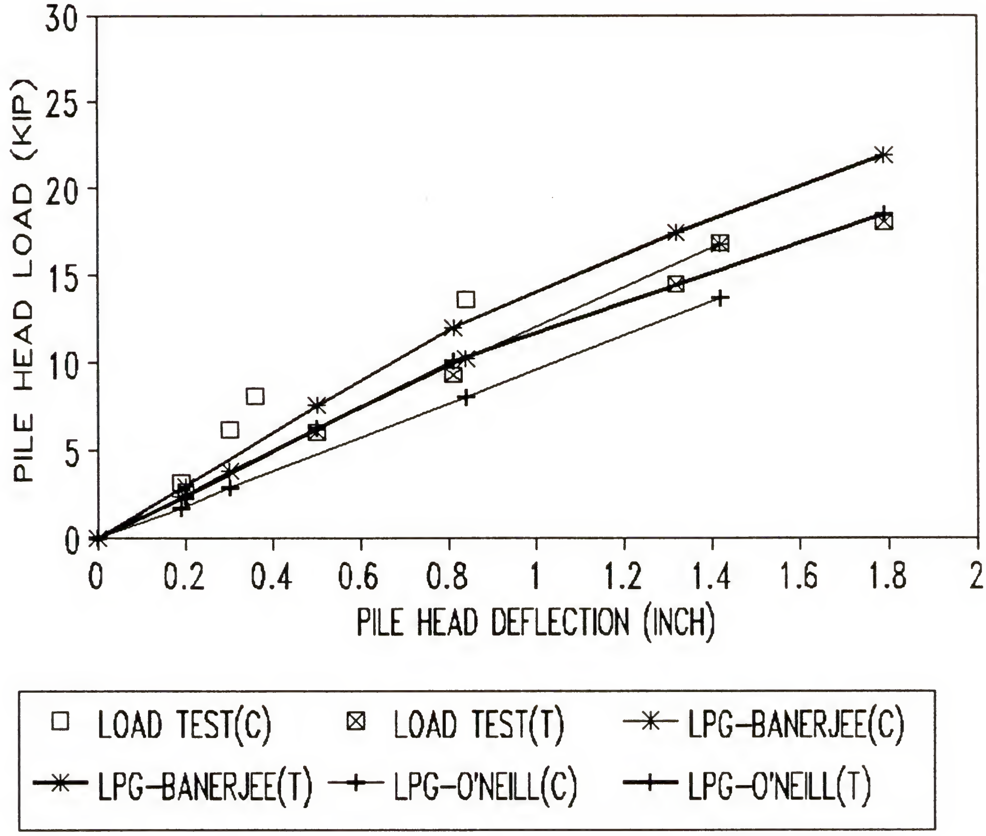


Figure 4.11.--Continued.
(b) Pile #2;

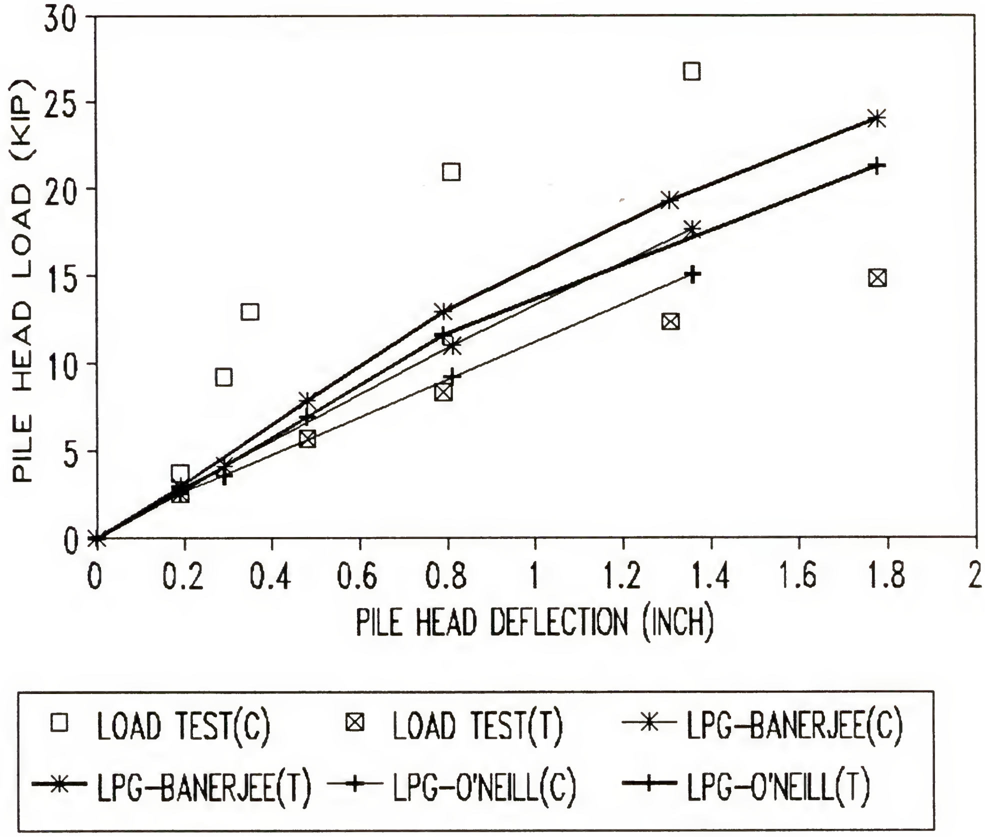


Figure 4.11.--Continued.
(c) Pile #3;

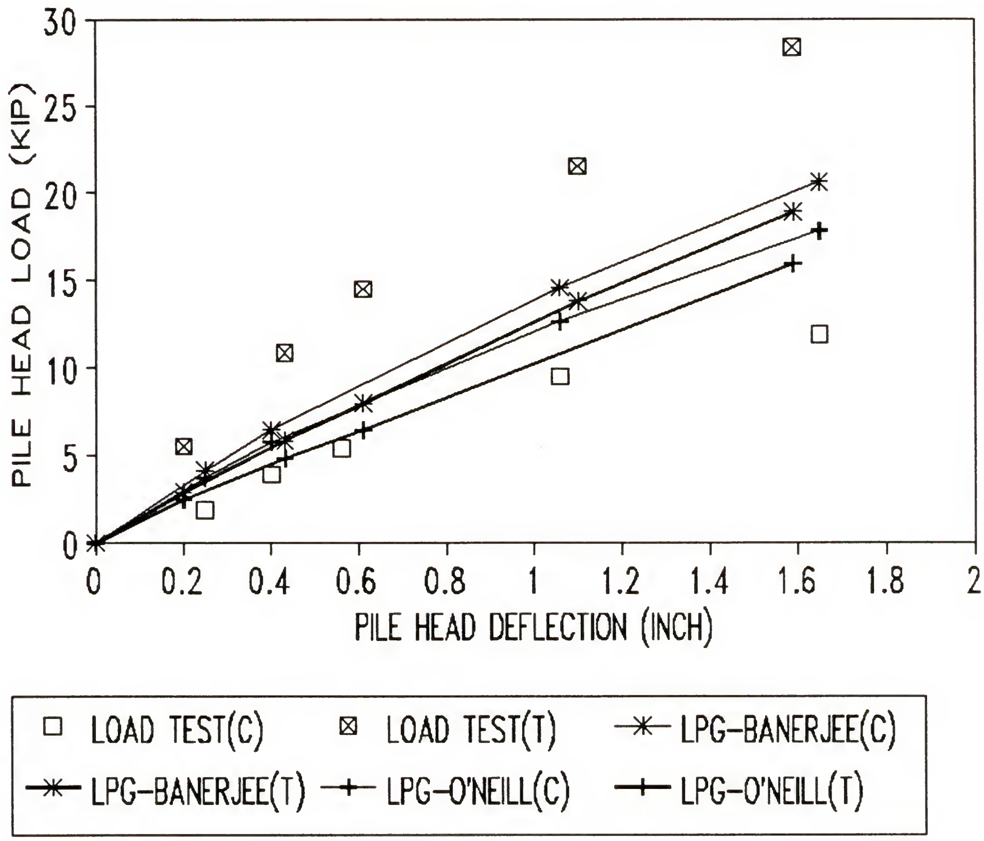


Figure 4.11.--Continued.
(d) Pile #4;

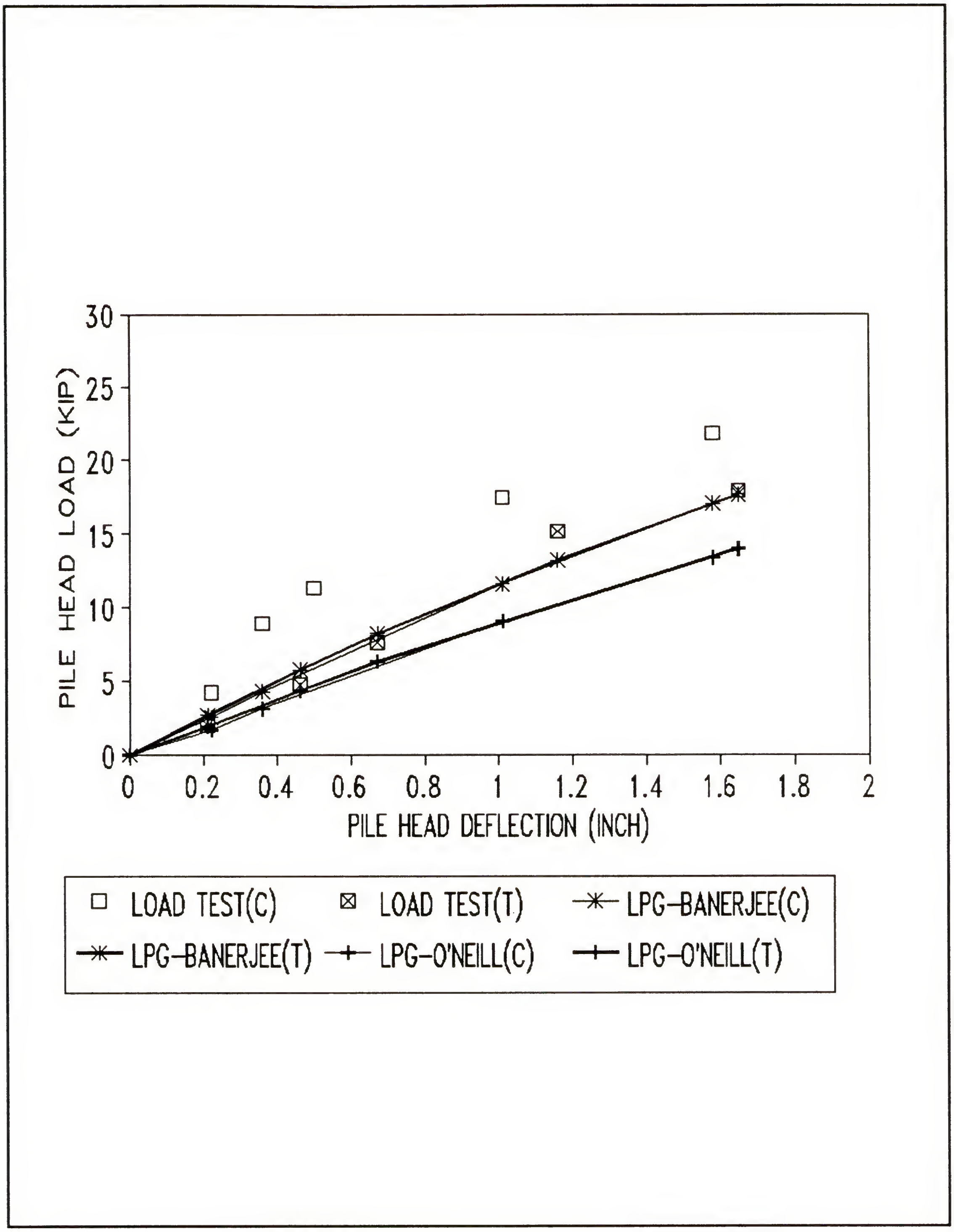


Figure 4.11.--Continued.
(e) Pile #5;

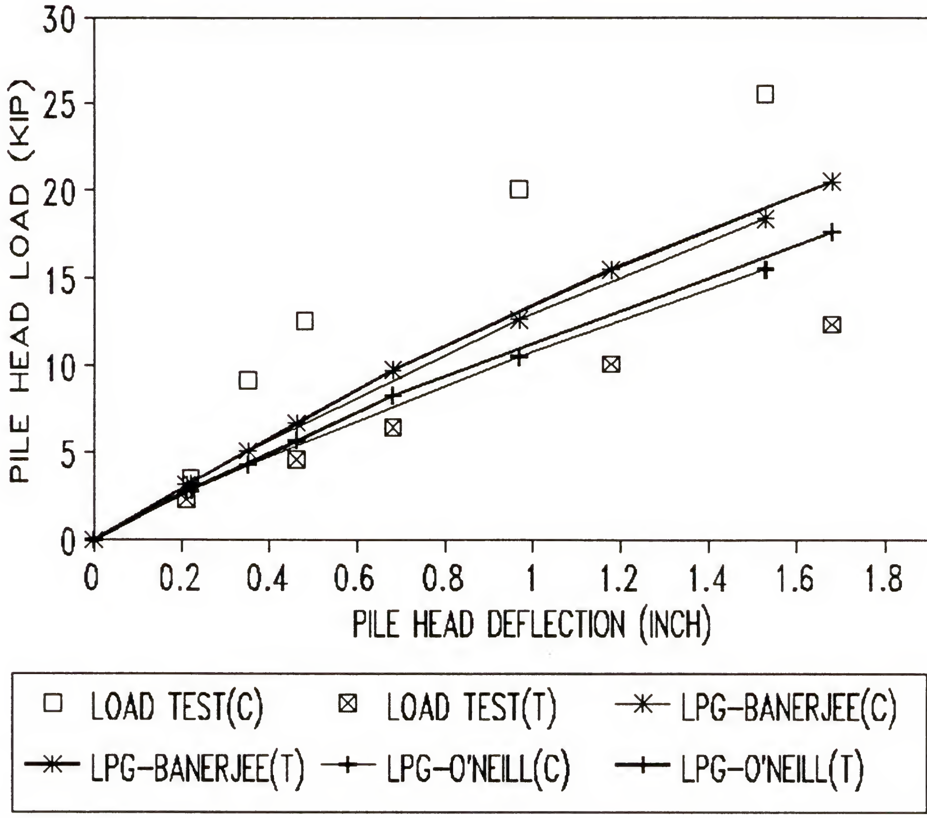


Figure 4.11.--Continued.
(f) Pile #6;

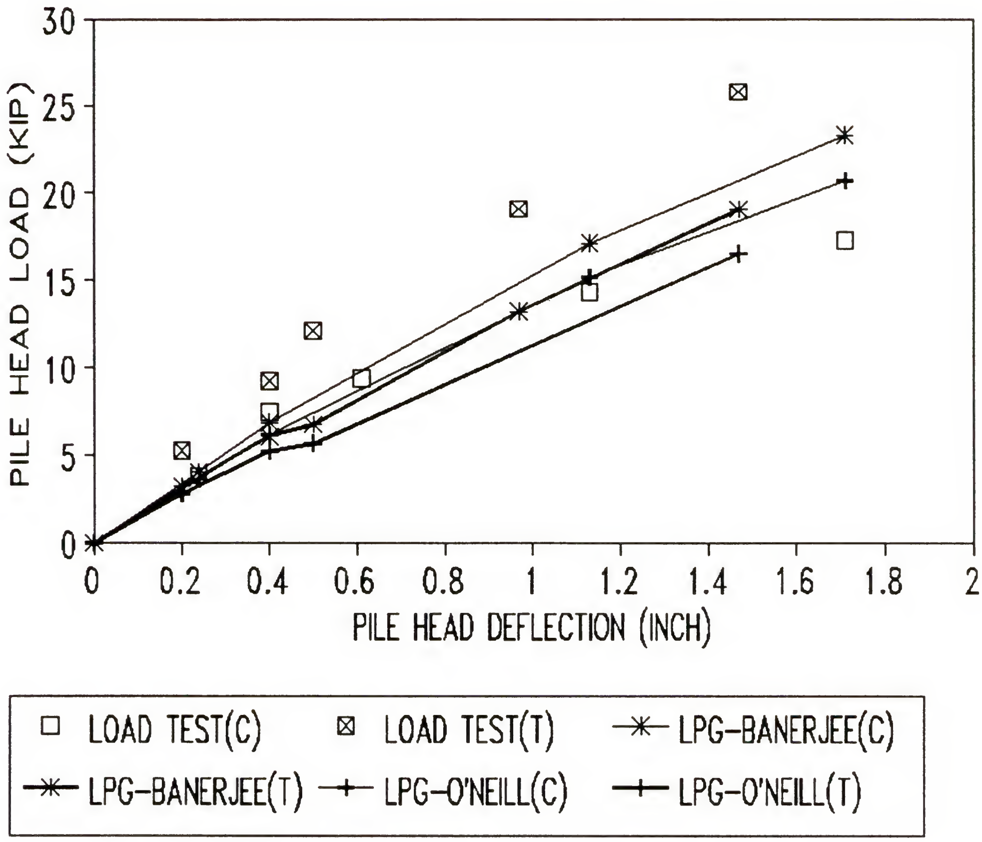


Figure 4.11.--Continued.
(g) Pile #7;

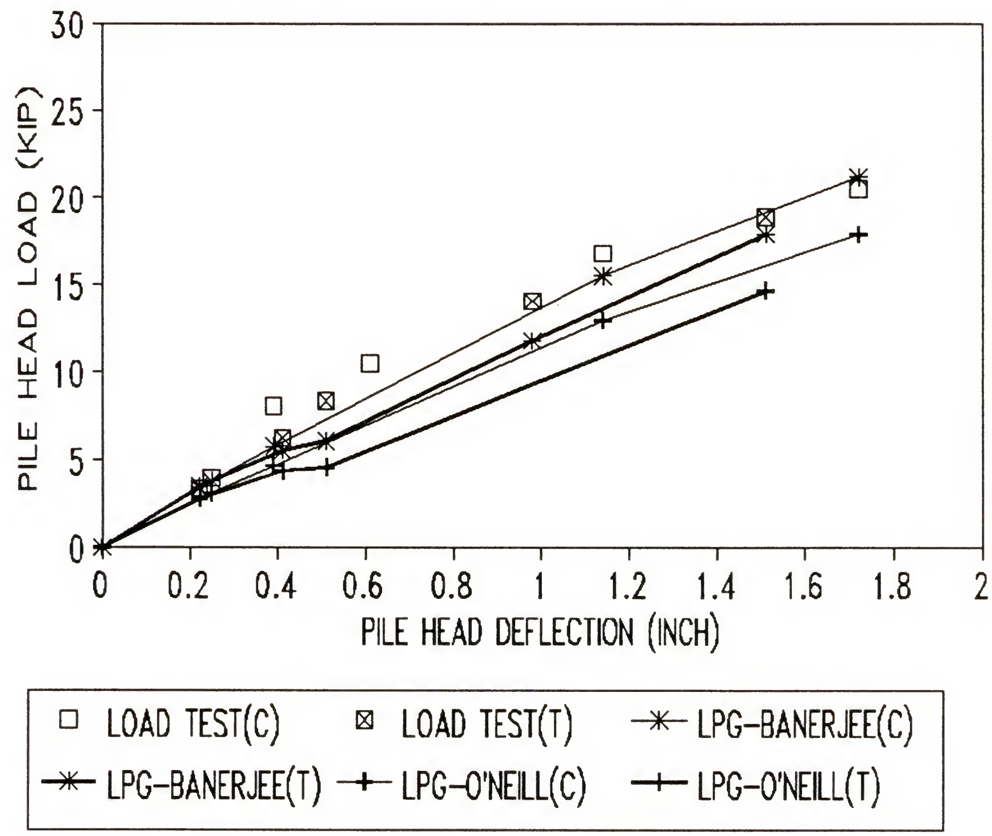


Figure 4.11.--Continued.
(h) Pile #8;

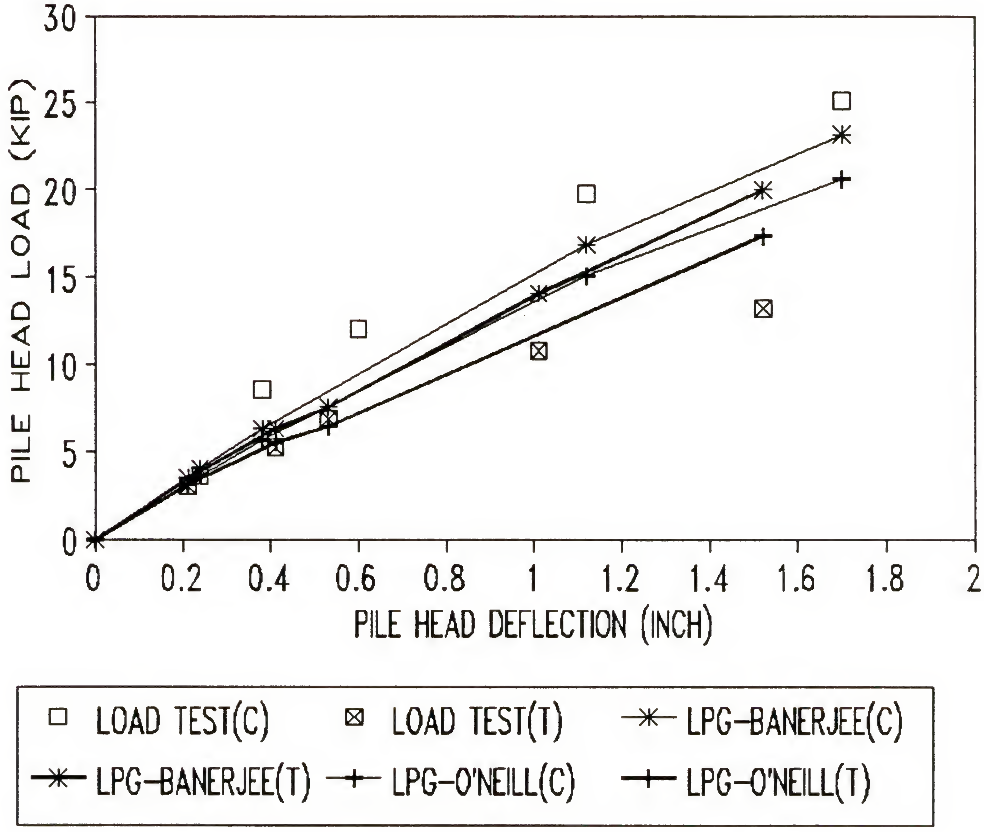


Figure 4.11.--Continued.
(i) Pile #9;

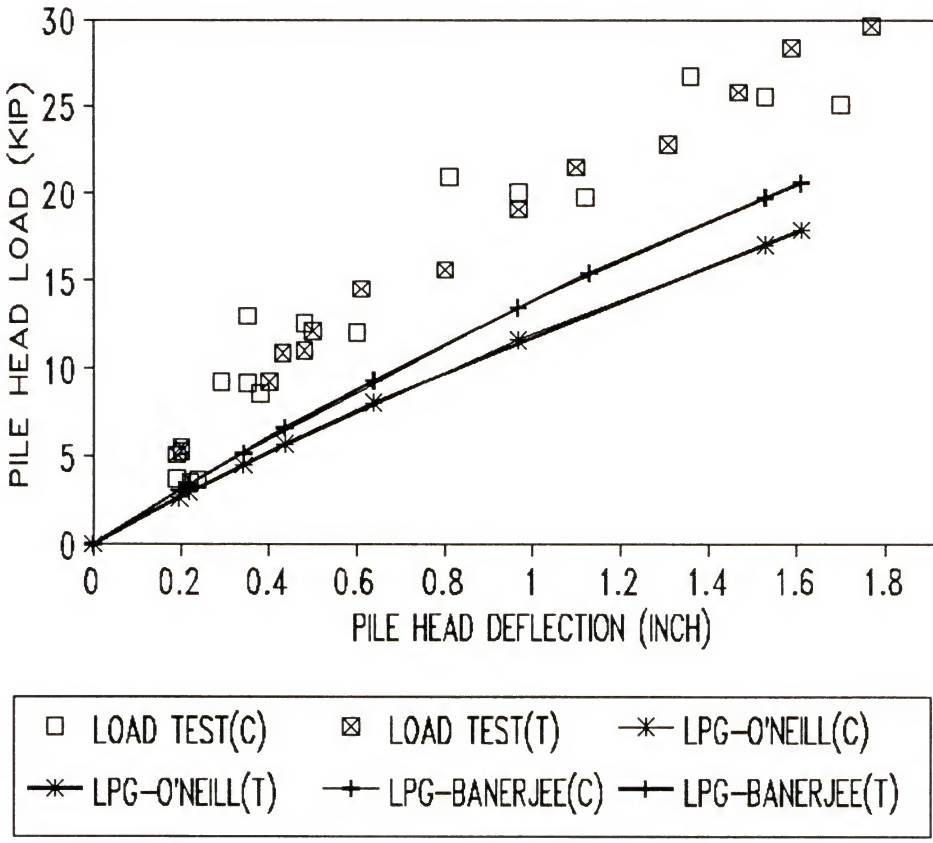


Figure 4.11.--Continued.
(j) Leading Row;

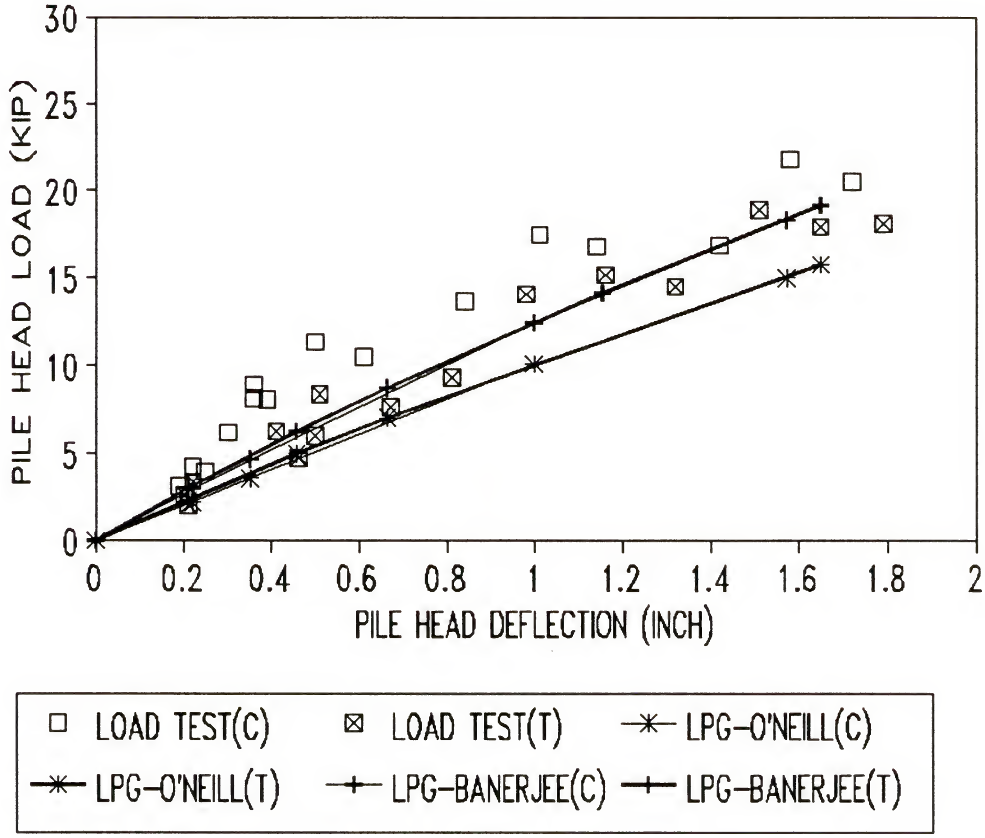


Figure 4.11.--Continued.
(k) Middle Row;

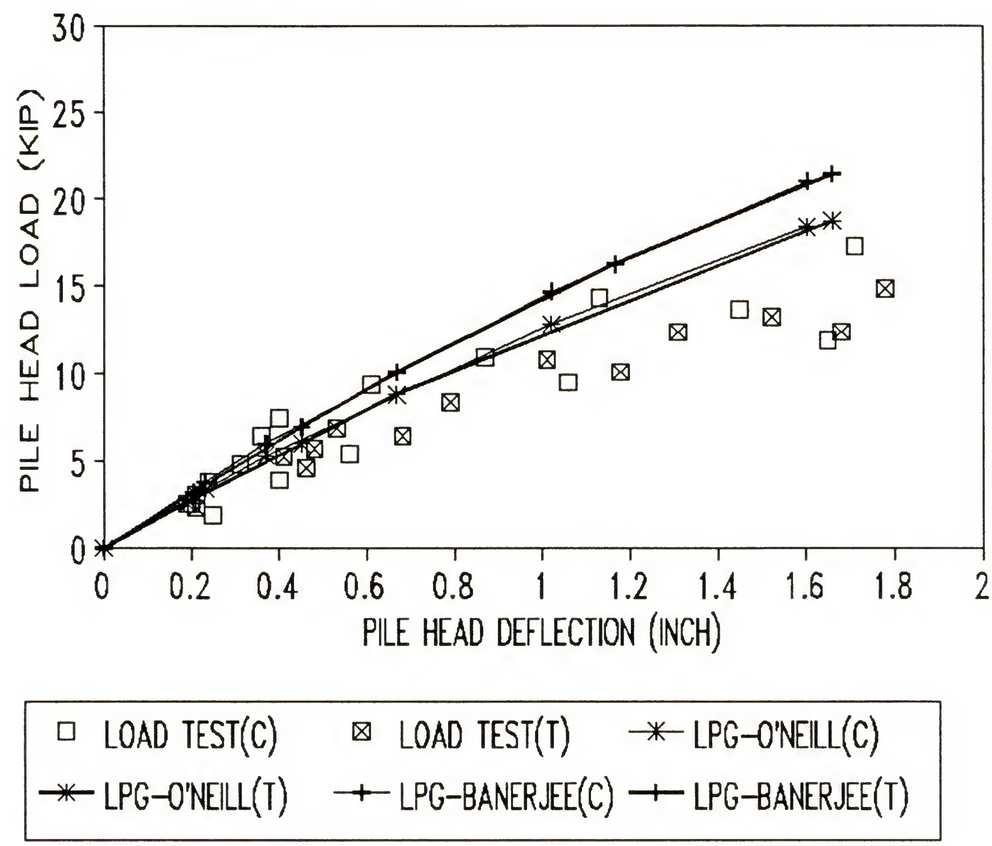


Figure 4.11.--Continued.
(l) Trailing Row;

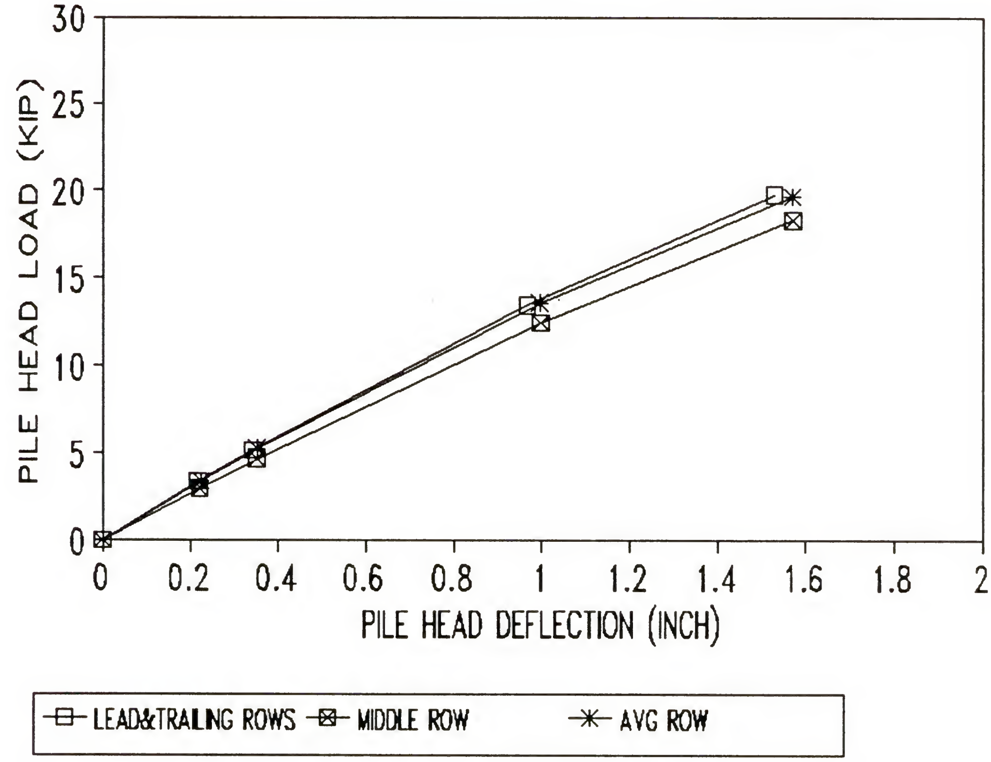


Figure 4.11.--Continued.
(m) Leading, Middle and Trailing Rows and Average Row [as predicted by LPG-Banerjee];

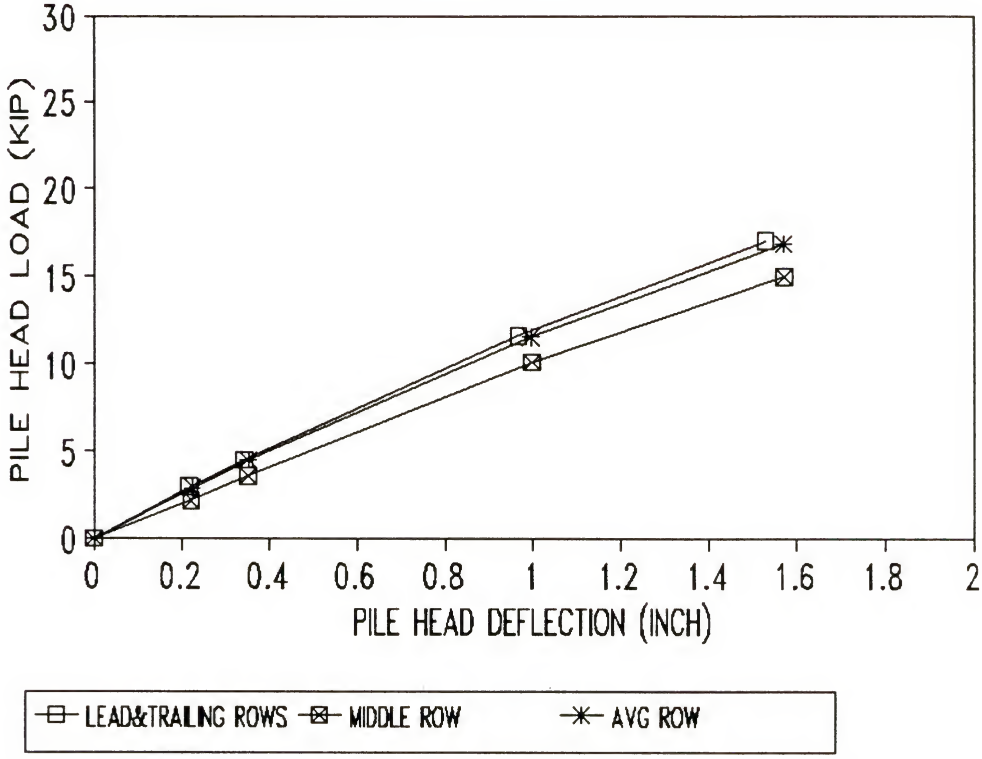


Figure 4.11.--Continued.
(n) Leading, Middle and Trailing Rows and Average Row [as predicted by LPG-O'Neill];

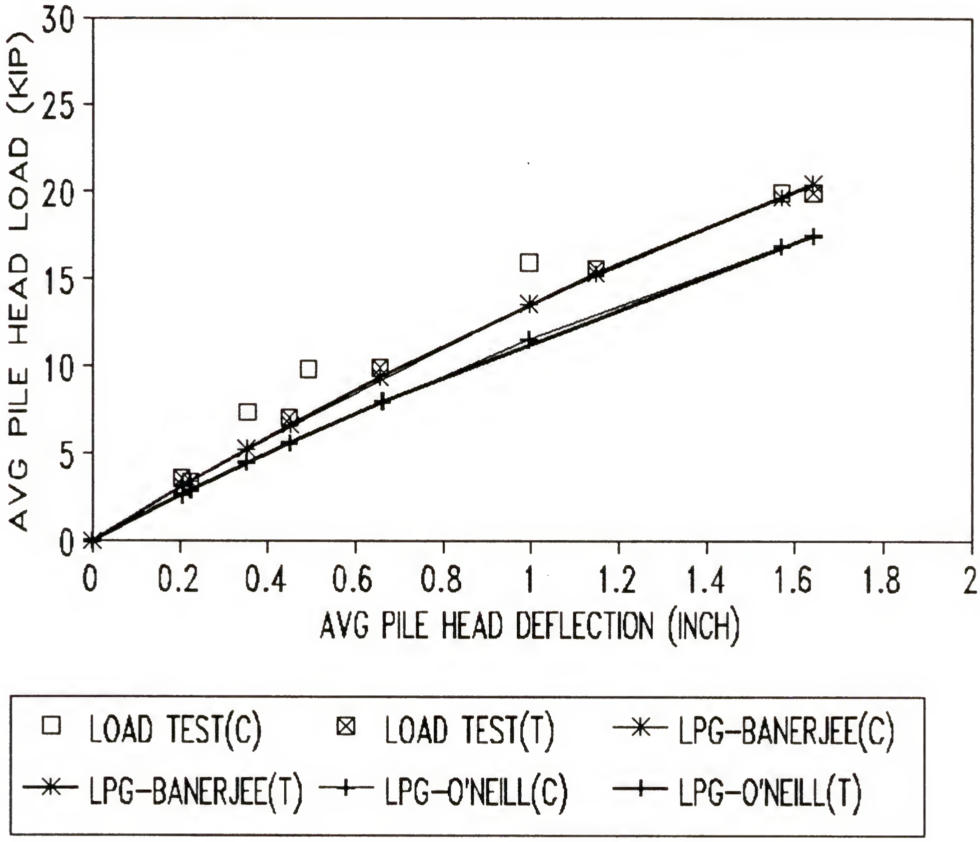


Figure 4.11.--Continued.
(o) Average pile

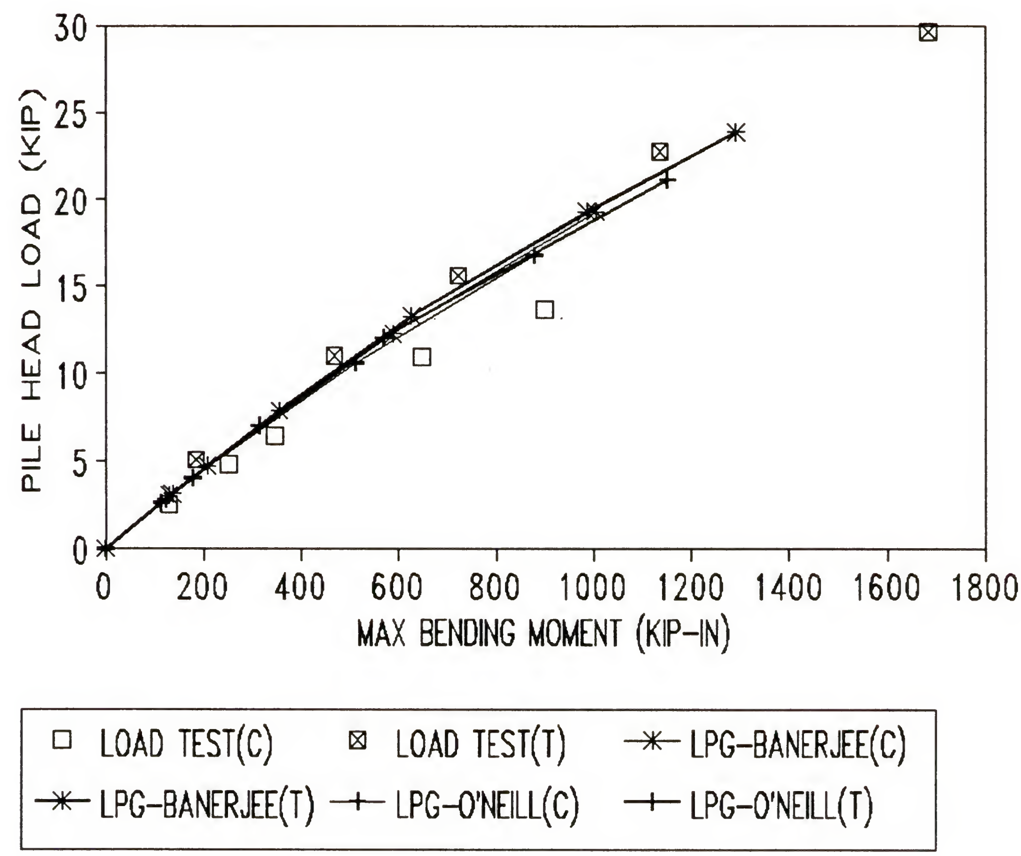


Figure 4.12. Pile-Head Load Vs Maxmimum Bending Moment for the Houston, Texas Pile Group for Cycle #1.
(a) Pile #1;

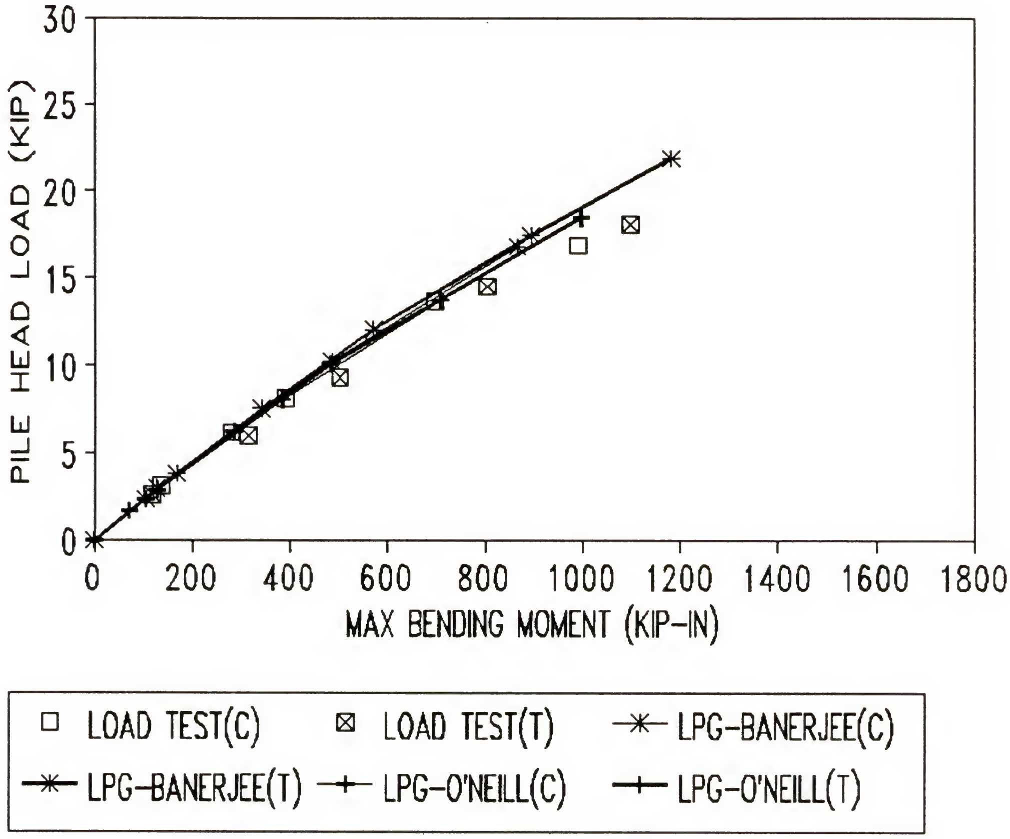


Figure 4.12.--Continued.
(b) Pile #2;

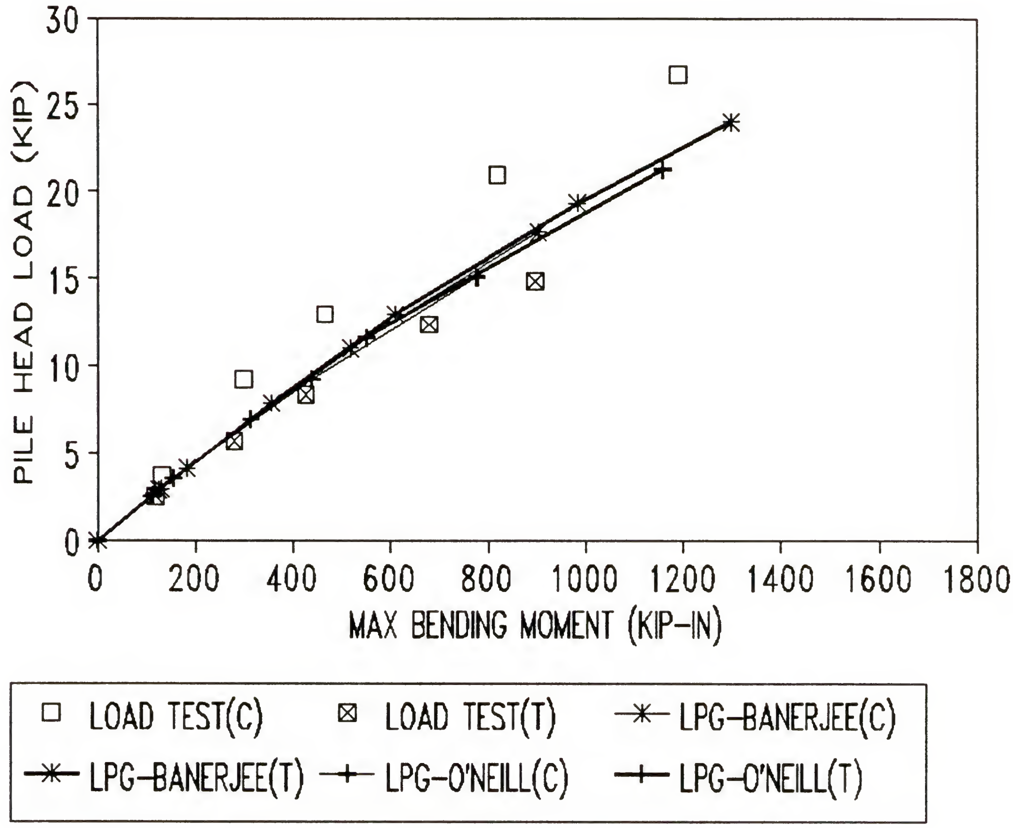


Figure 4.12.--Continued.
(c) Pile #3;

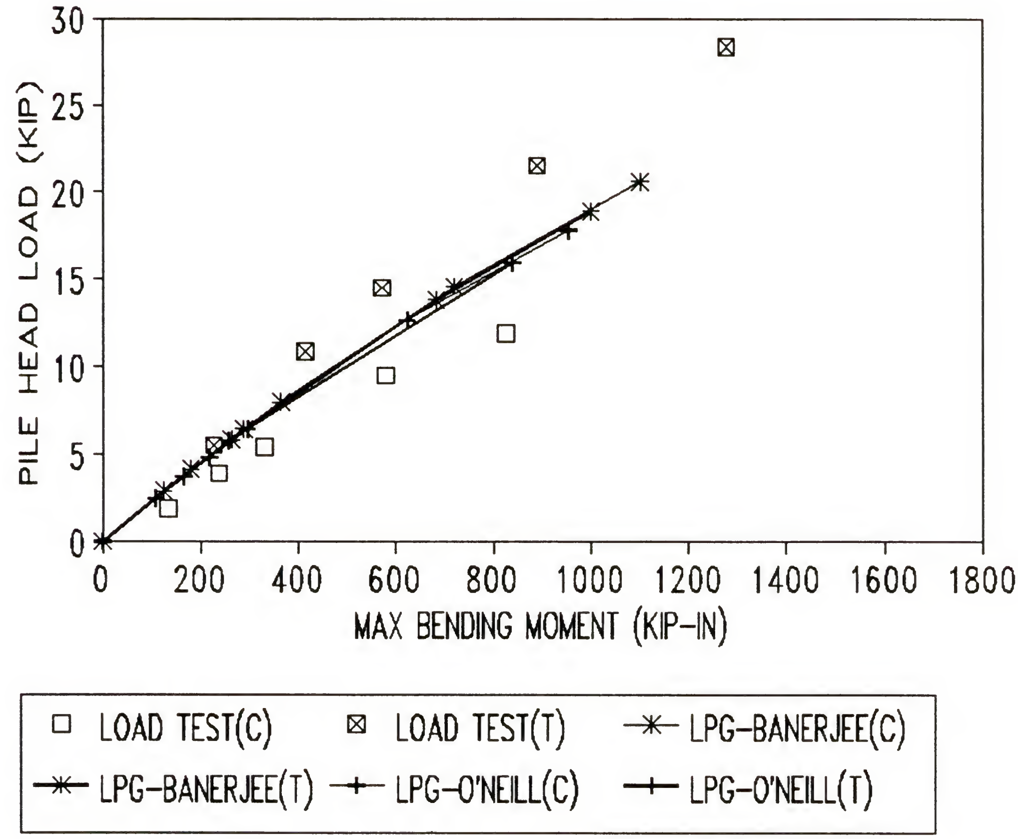


Figure 4.12.--Continued.
(d) Pile #4;

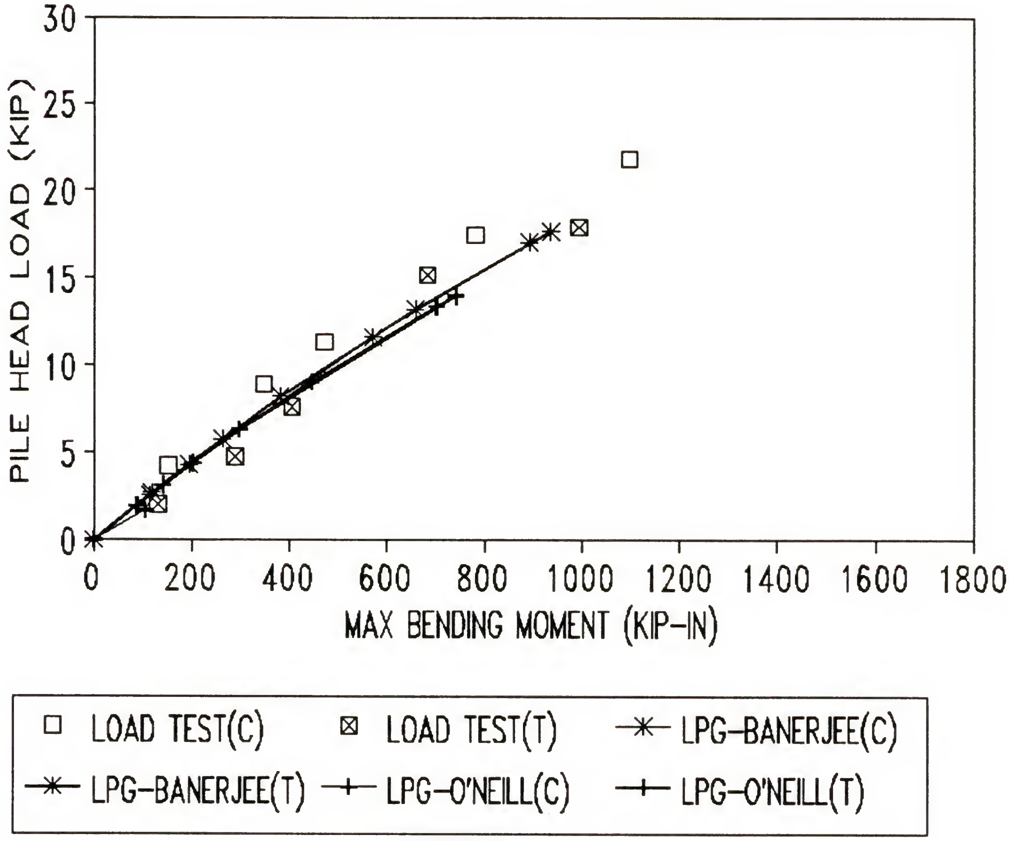


Figure 4.12.--Continued.
(e) Pile #5;

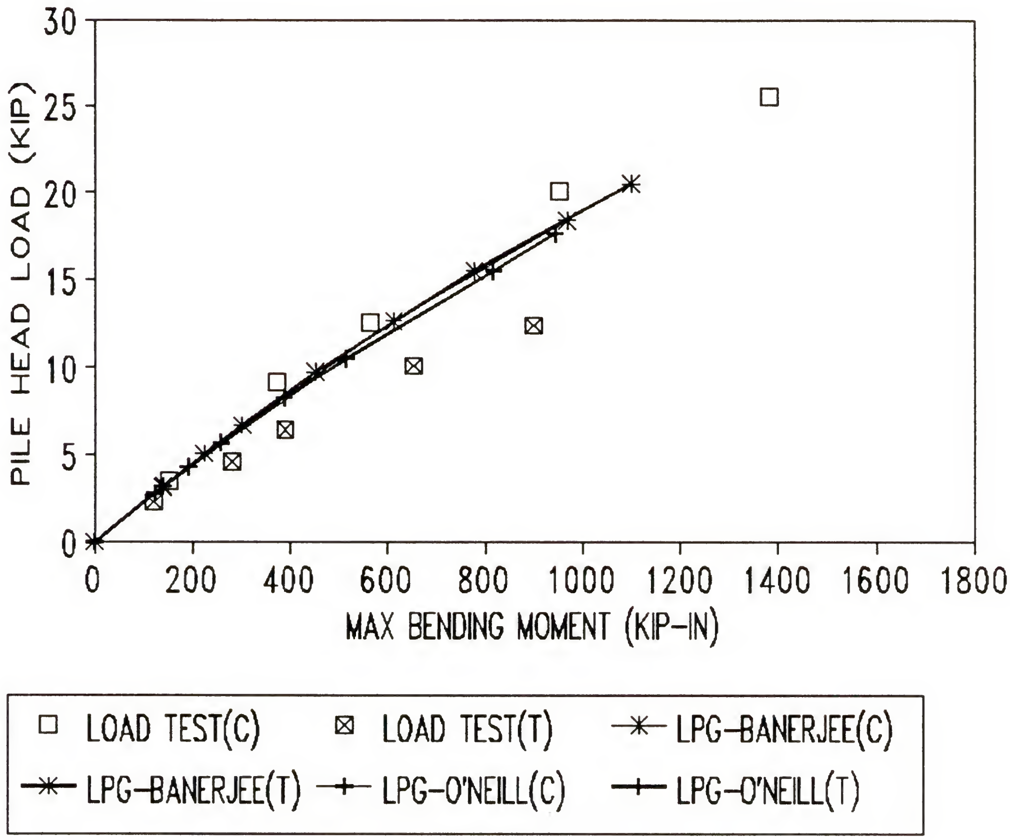


Figure 4.12.--Continued.
(f) Pile #6;

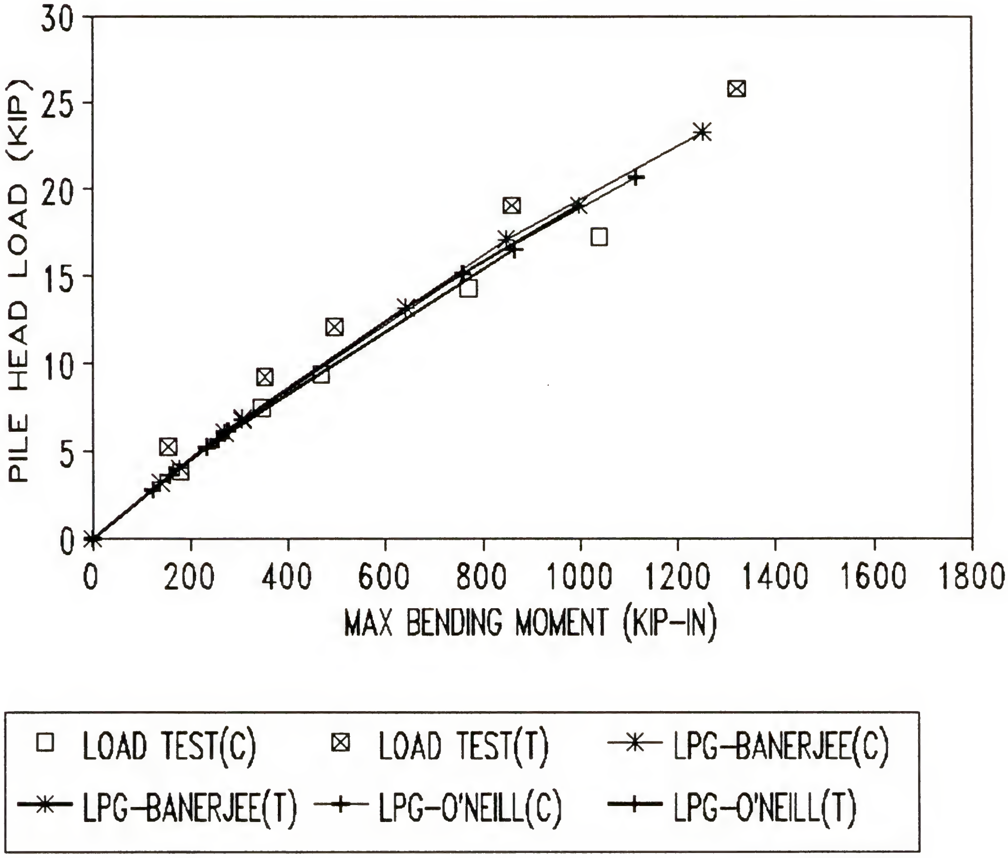


Figure 4.12.--Continued.
(g) Pile #7;

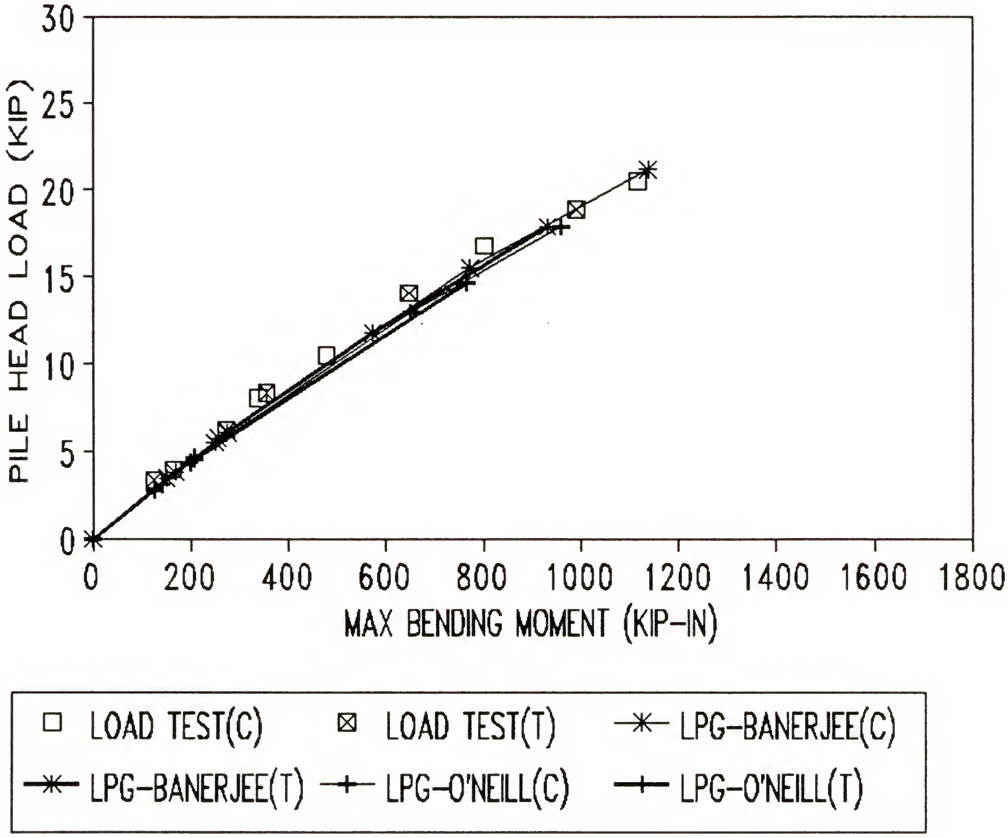


Figure 4.12.--Continued.
(h) Pile #8;

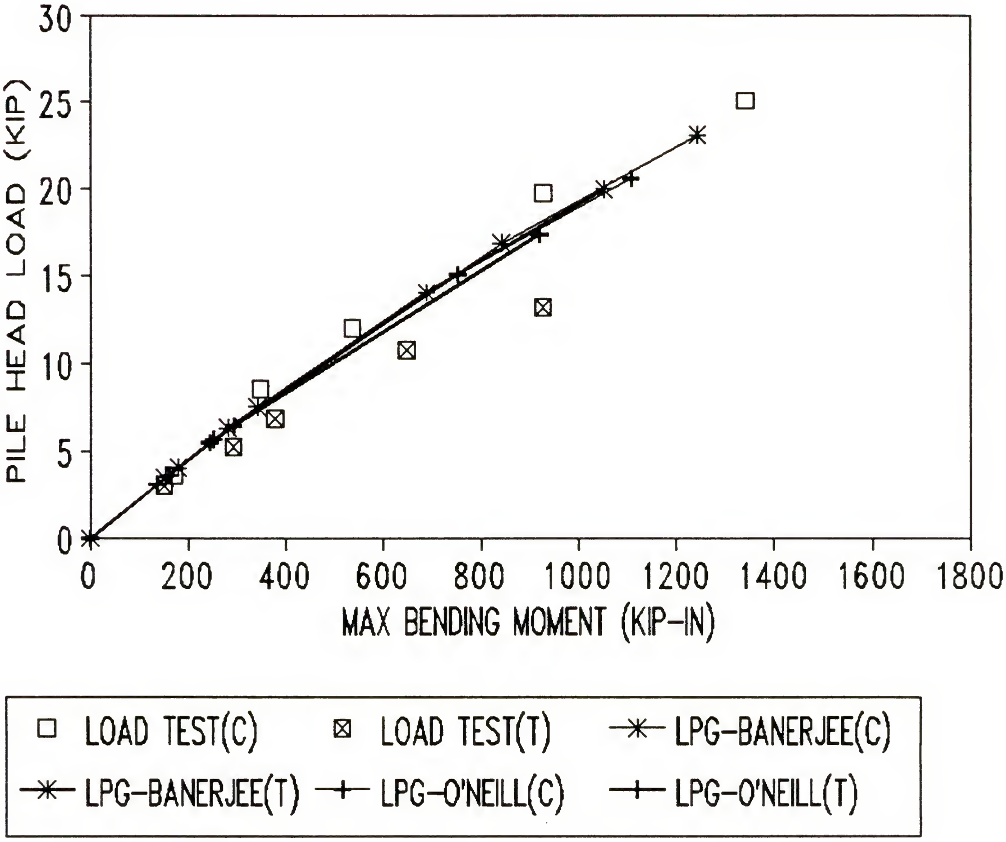


Figure 4.12.--Continued.
(i) Pile #9;

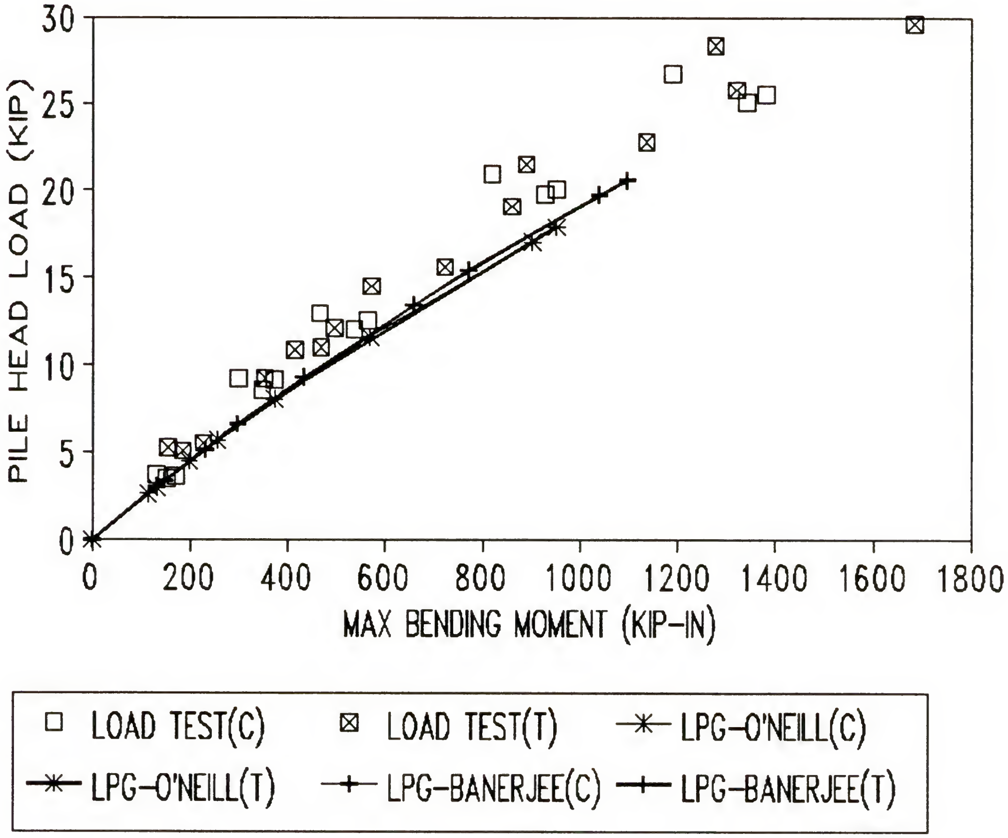


Figure 4.12.--Continued.
(j) Leading Row;

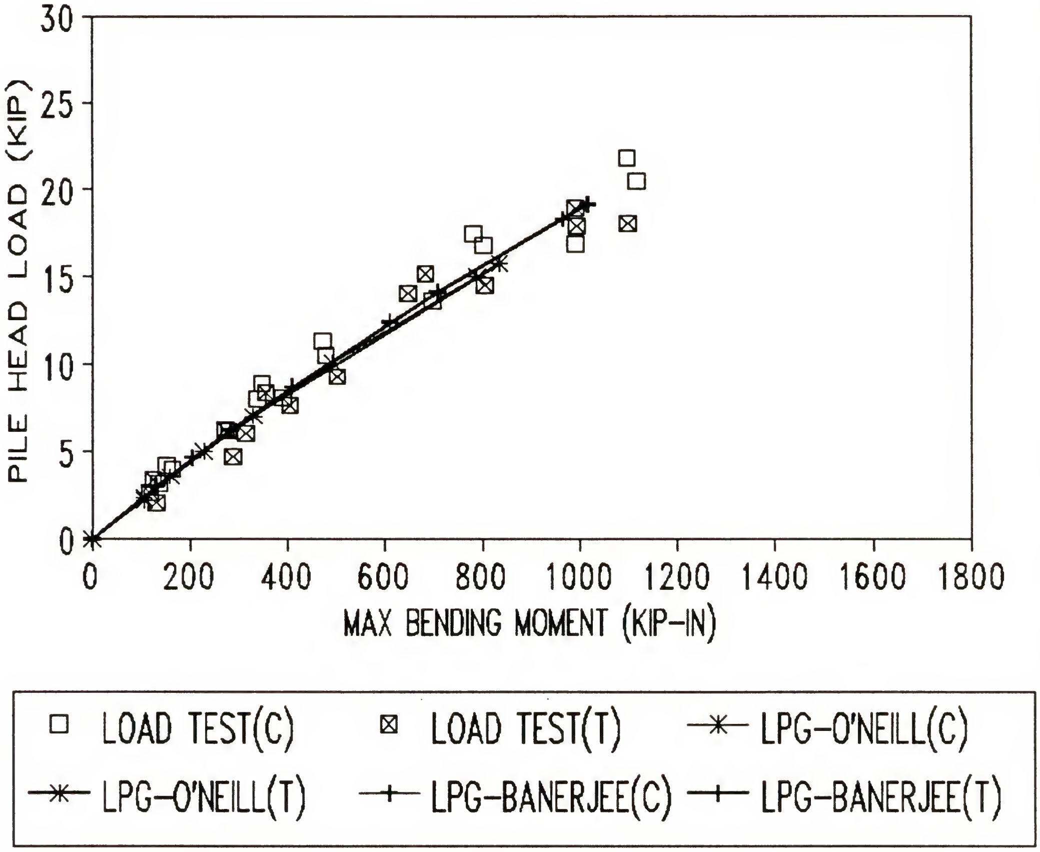


Figure 4.12.--Continued.
(k) Middle Row;

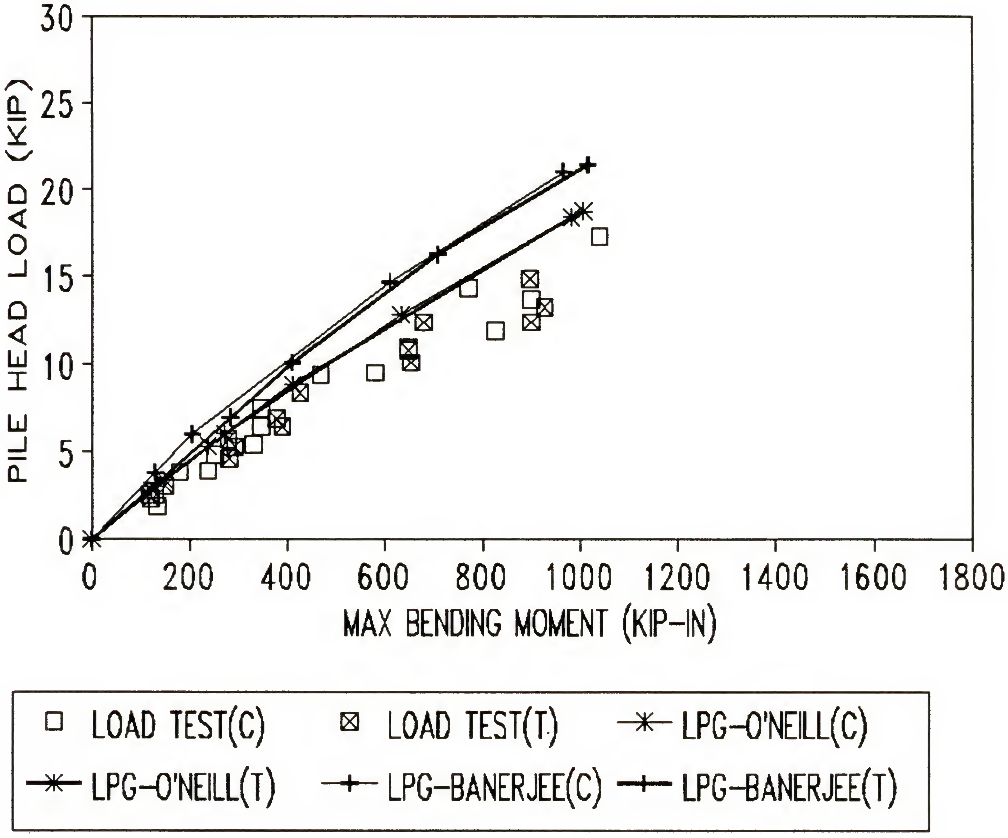


Figure 4.12.--Continued.
(l) Trailing Row;

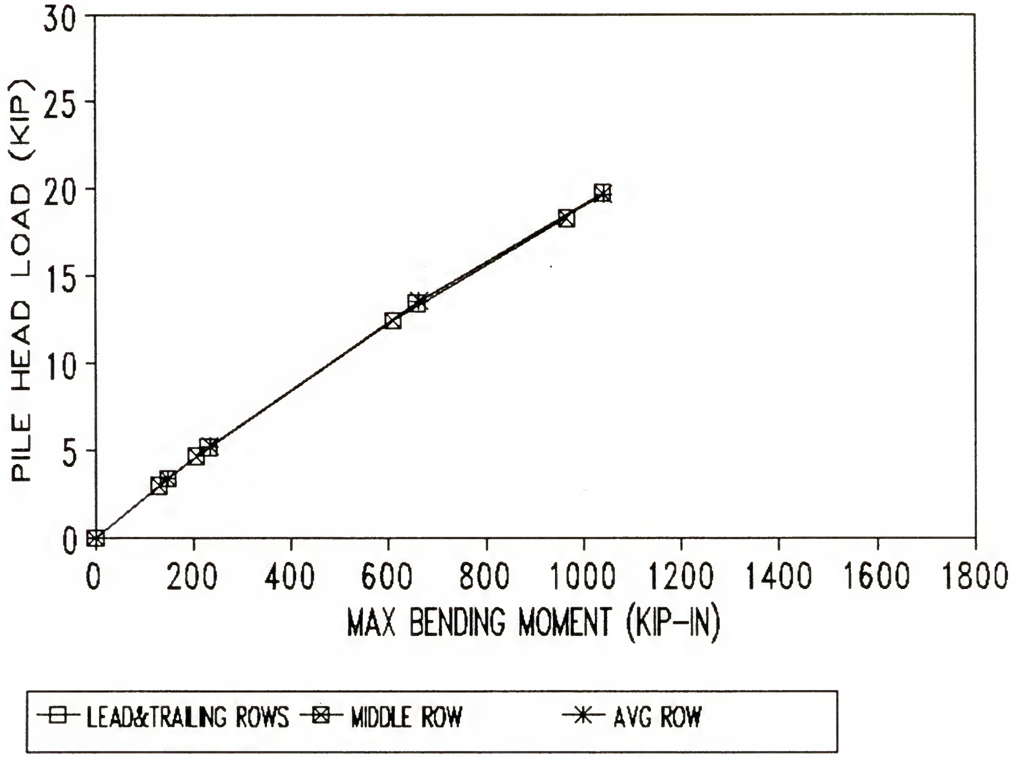


Figure 4.12.--Continued.
(m) Leading, Middle and Trailing Rows and Average Row [as predicted by LPG-Banerjee];

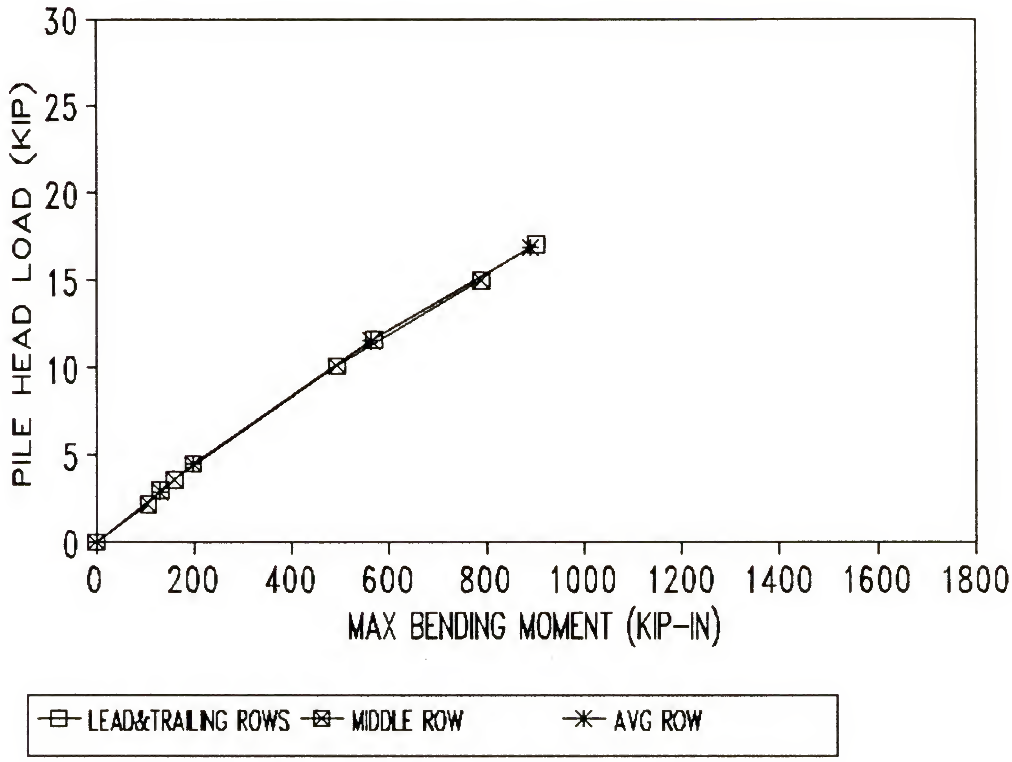


Figure 4.12.--Continued.
(n) Leading, Middle and Trailing Rows and Average Row [as predicted by LPG-O'Neill];

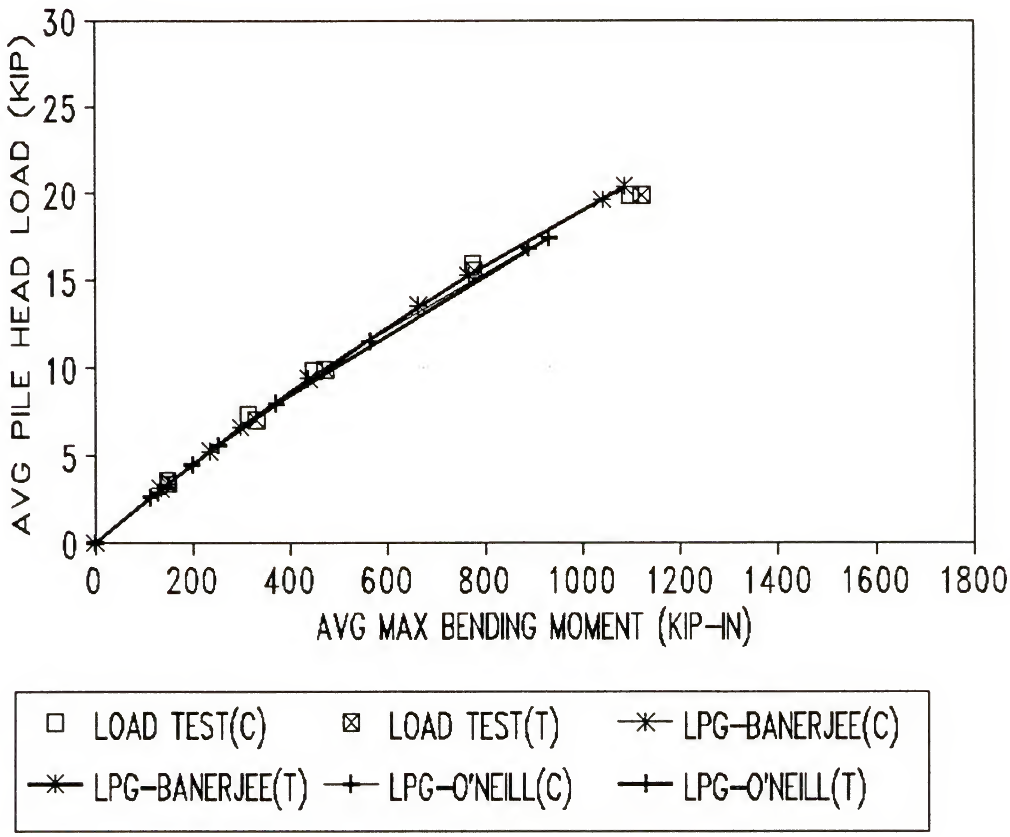


Figure 4.12.--Continued.
(o) Average pile

from the figures that the program LPG, under predicts, fairly well and over predicts the load for the leading, middle and trailing rows of the group respectively for both Gs values. Figures 4.11 (m) and (n) shows the response of individual rows by the LPG-O'Neill and LPG-Banerjee. It can be noticed from the figures that the leading and trailing row respond identically and they have higher pile-head load than middle row's. Figure 4.11 (o) presents the response of an average pile. From the figure, it is observed that the pile-head load for an average pile of the group predicted by LPG-Banerjee is very good while the load predicted by LPG-O'Neill is lower when compared to field data.

Figures 4.12 (a)-(o) presents the pile-head load-maximum bending moment response of each pile, each individual row and an average pile of the group. The figures exhibit the same behaviors as those for pile-head load-deflection response of the group discussed earlier. Over all the pile-head load-maximum bending moment response of an average pile predicted by LPG-Banerjee is the best.

4.4.2 Cyclic Loading

Figures 4.13 and 4.14 present the pile-head load-deflection and pile-head load-maximum bending moment responses of the single pile for cycle #100 predicted by LPG. The responses match well with the field data.

Figures 4.15 (a)-(o) present the pile-head load-deflection response and Figures 4.16 (a)-(o) depict the

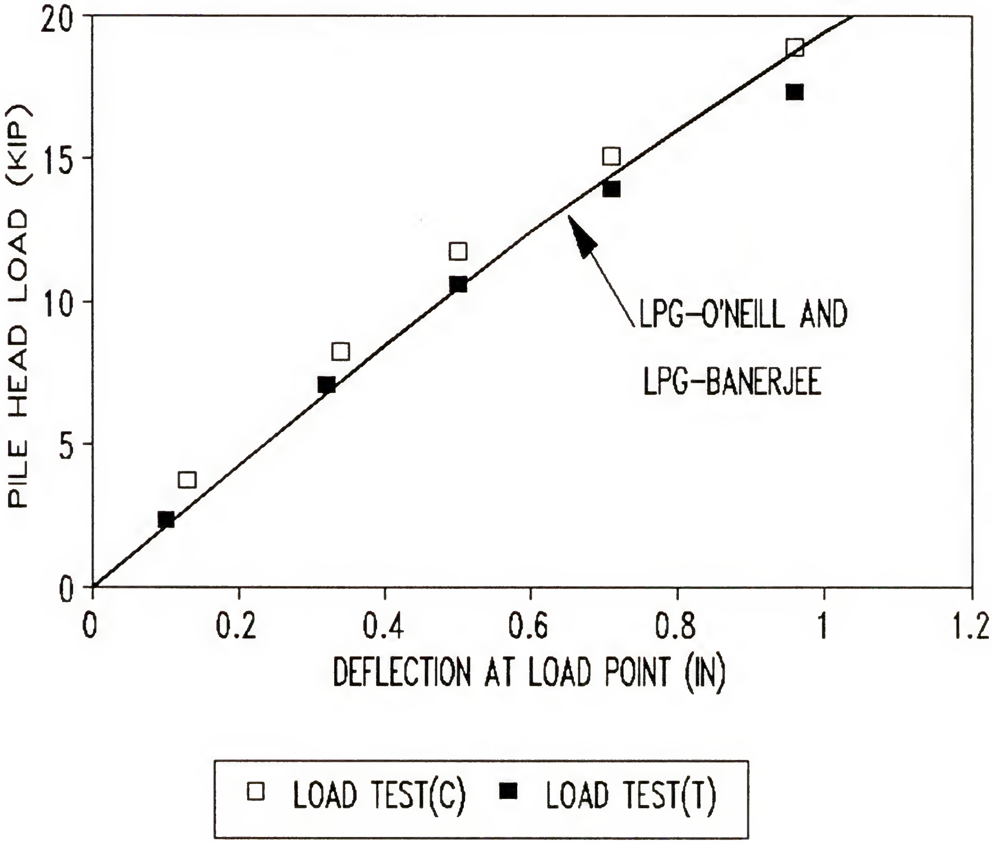


Figure 4.13. Pile-Head Load Vs Deflection for the Houston, Texas Single Pile for Cycle #100.

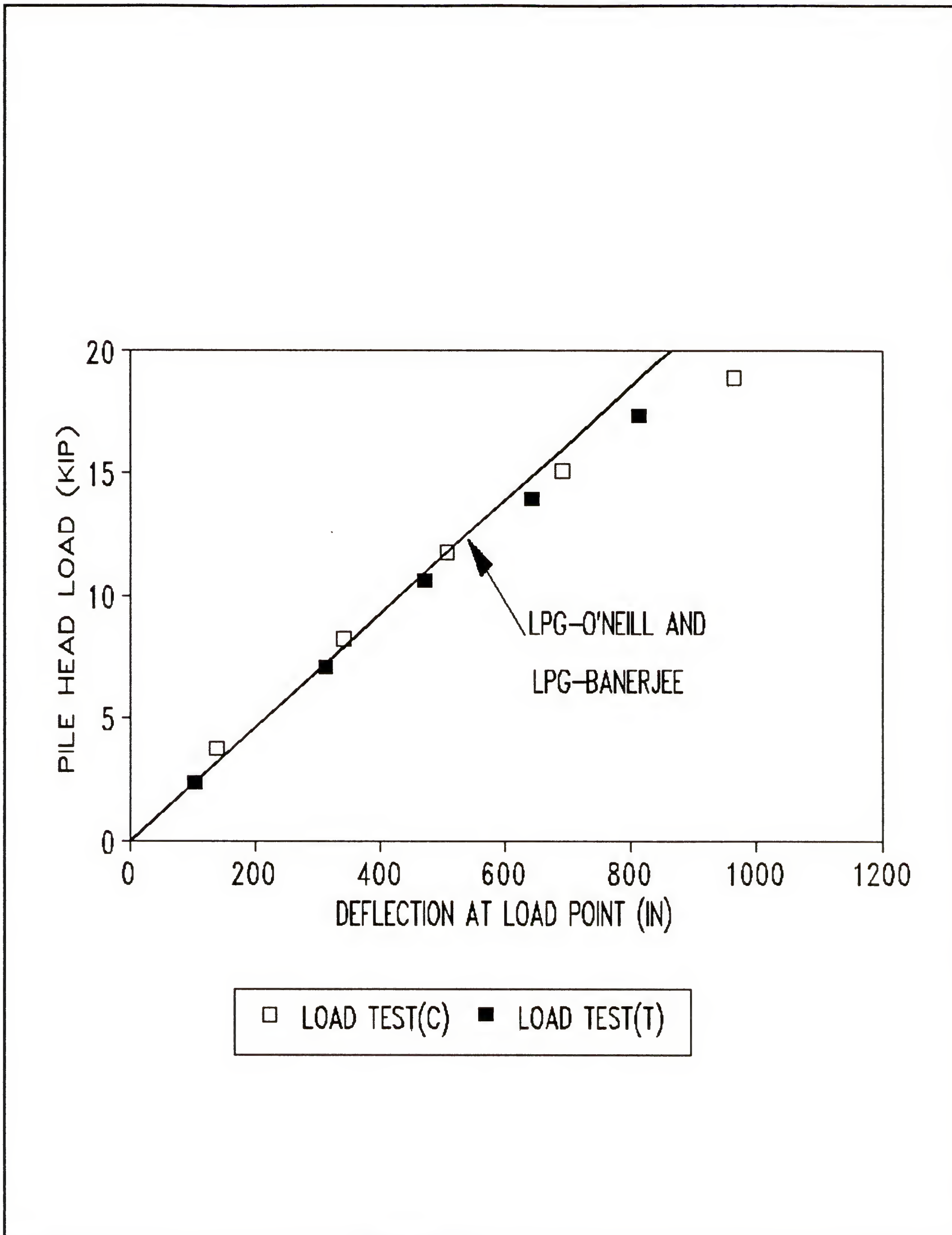


Figure 4.14. Pile-Head Load Vs Maximum Bending Moment for the Houston, Texas Single Pile for Cycle #100.

pile-head load-maximum bending moment response of the group.These figures exhibit behaviors very similar to those for static case discussed in section 4.4.1. From all the figures, it is observed that leading and trailing rows of piles behave identical and LPG-Banerjee predicts the response of an average pile in the group very well.

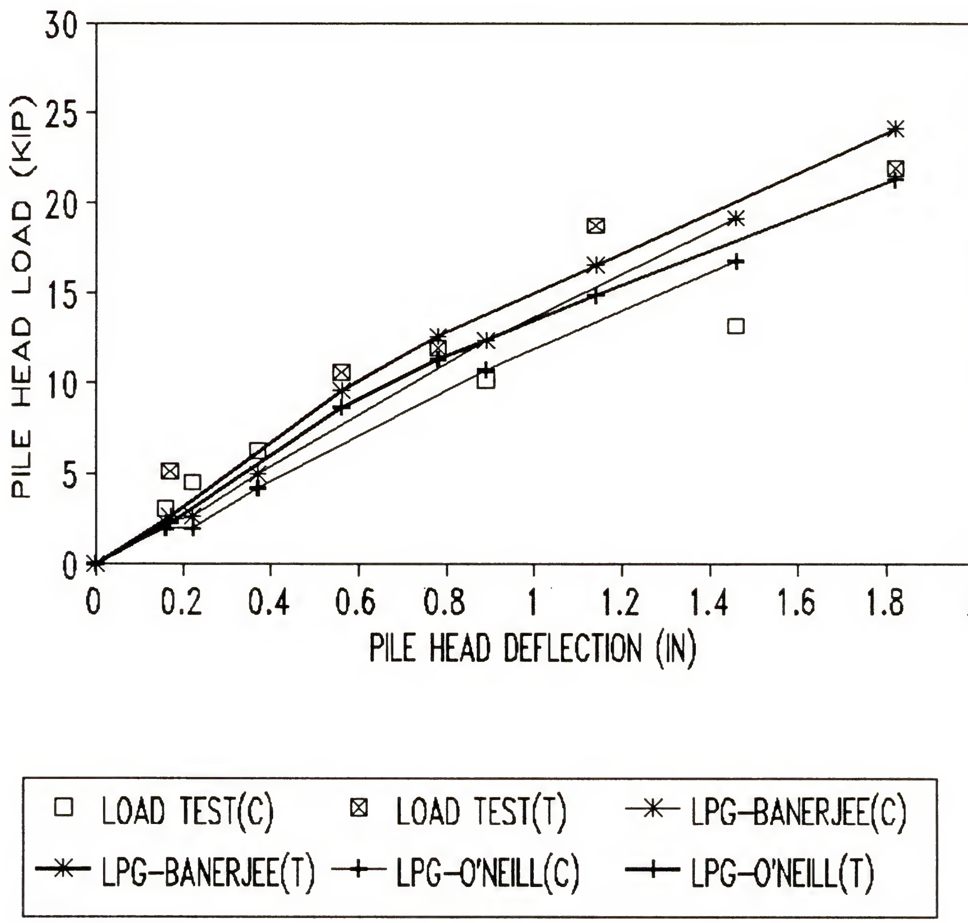


Figure 4.15. Pile-Head Load Vs Deflection for the Houston, Texas Pile Group for Cycle #100.
(a) Pile #1;

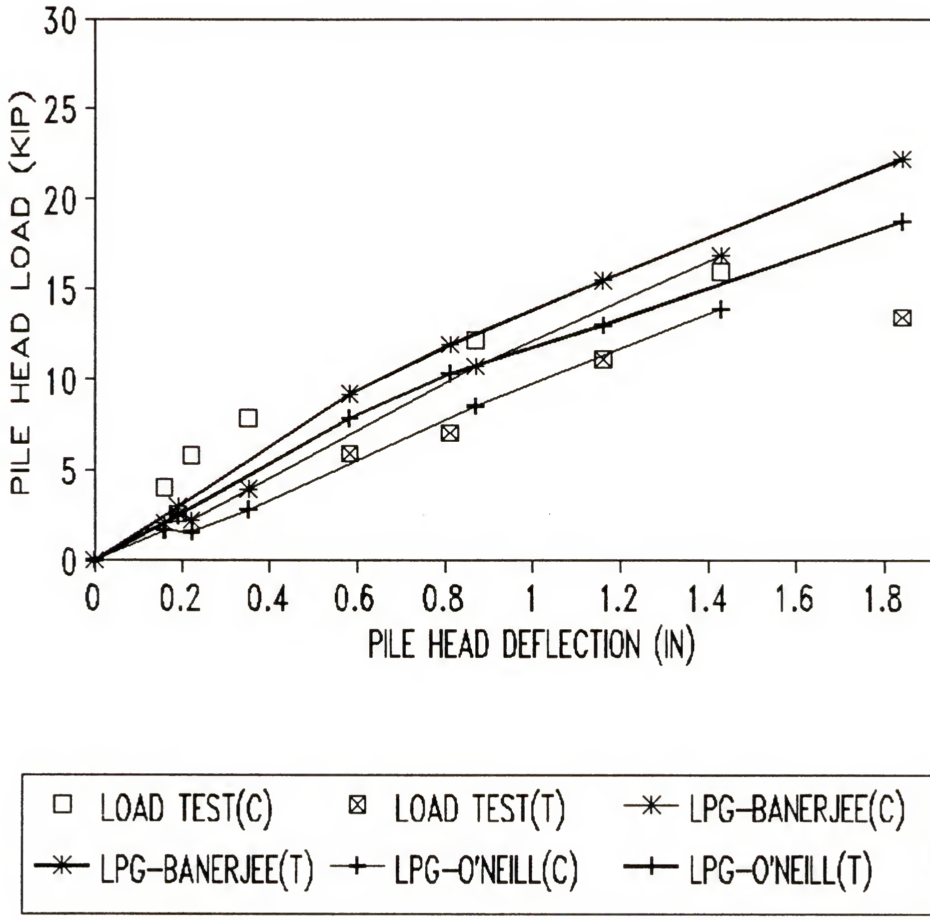


Figure 4.15.--Continued.
(b) Pile #2;

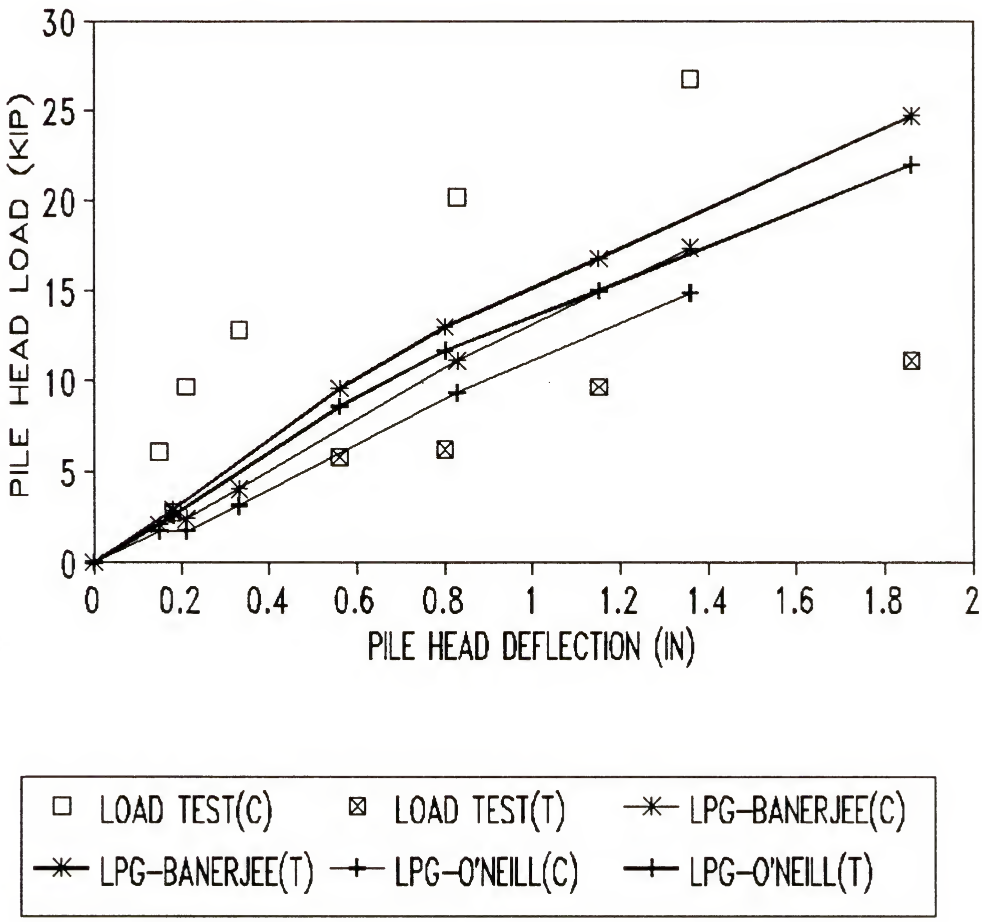


Figure 4.15.--Continued.
(c) Pile #3;

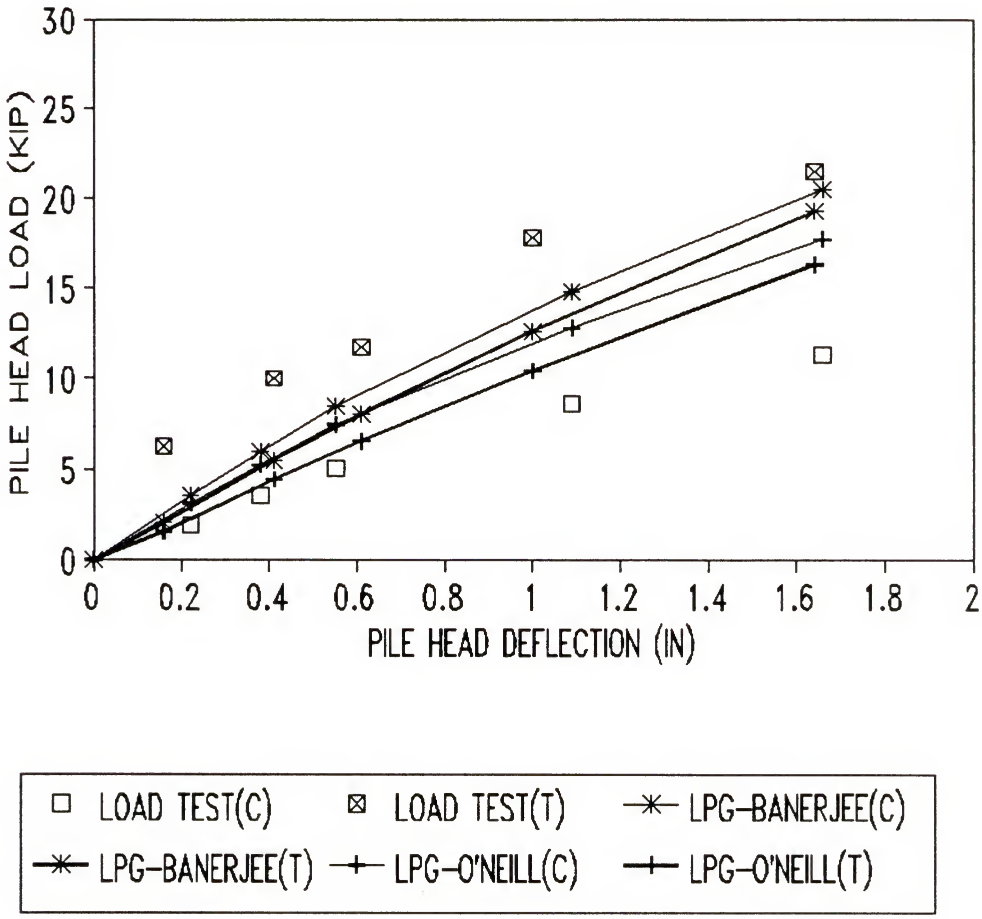


Figure 4.15.--Continued.
(d) Pile #4;

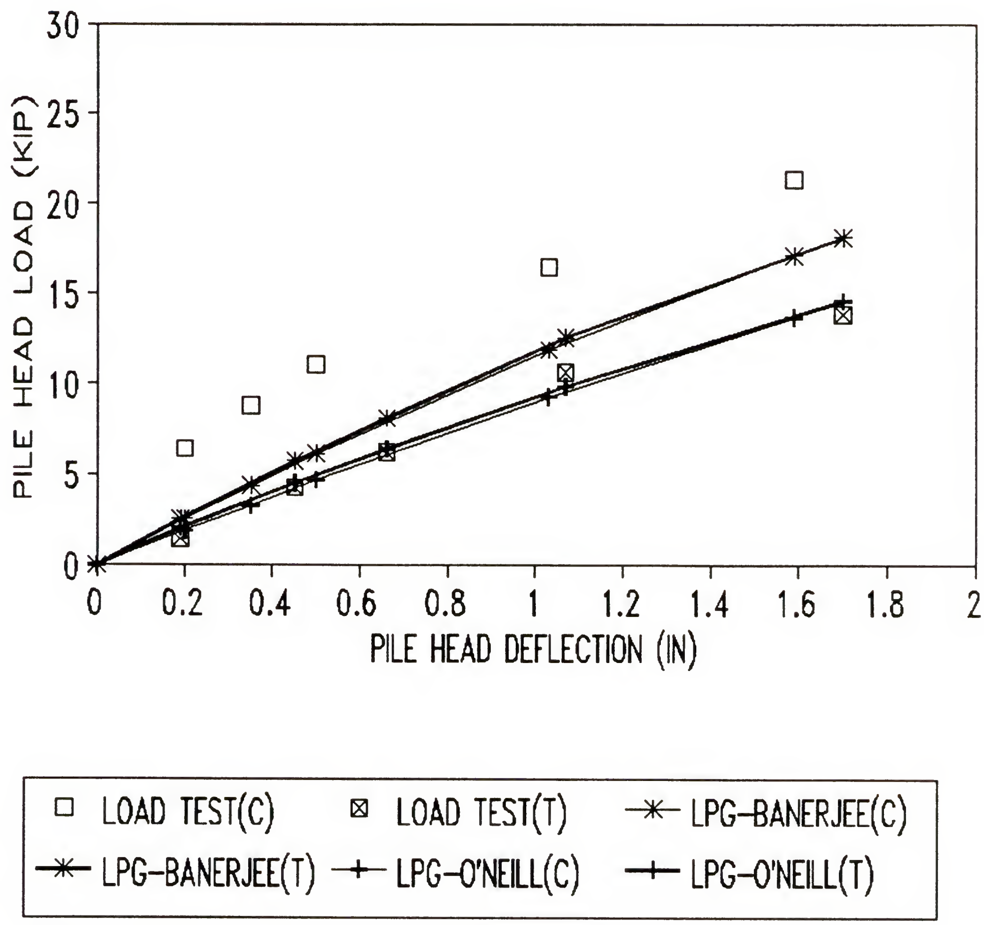


Figure 4.15.--Continued.
(e) Pile #5;

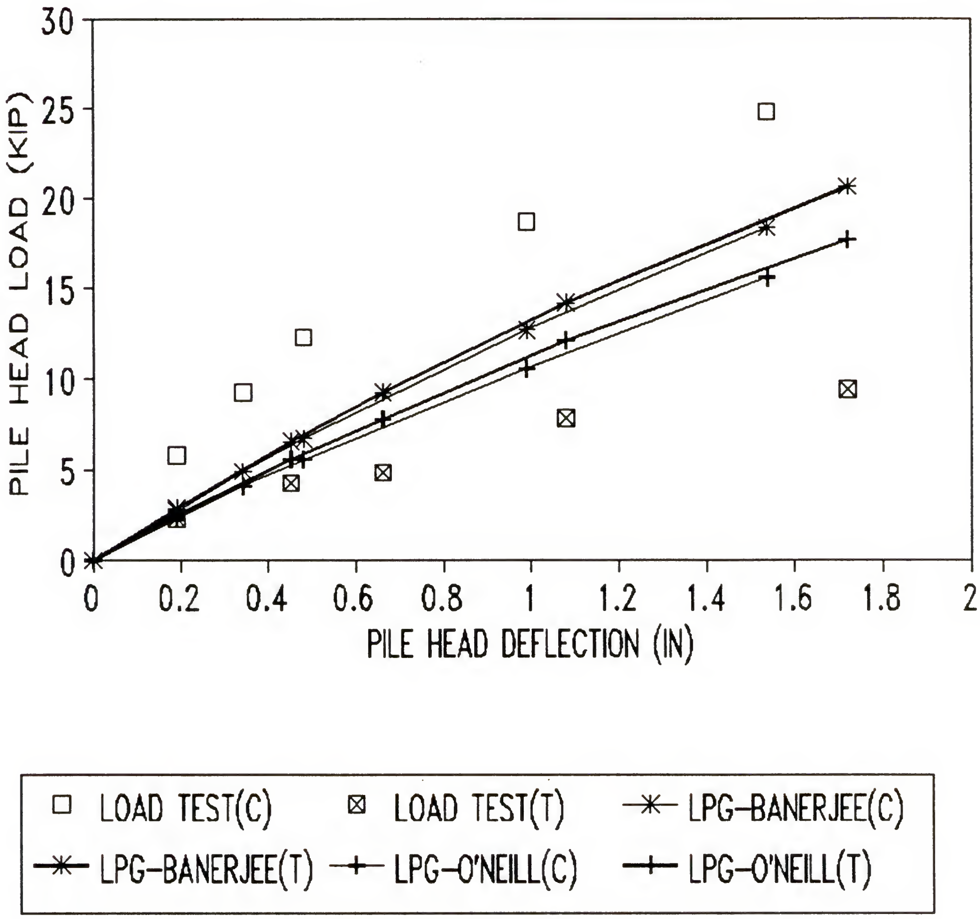


Figure 4.15.--Continued.
(f) Pile #6;

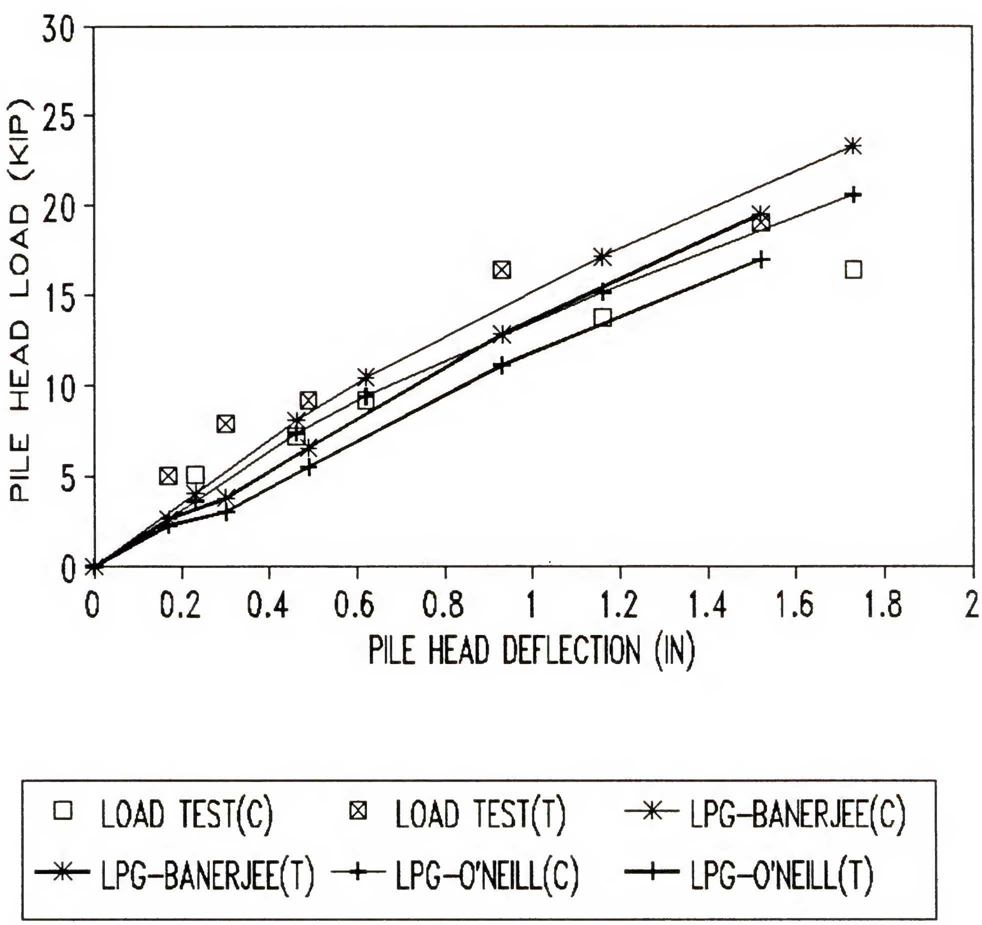


Figure 4.15.--Continued.
(g) Pile #7;

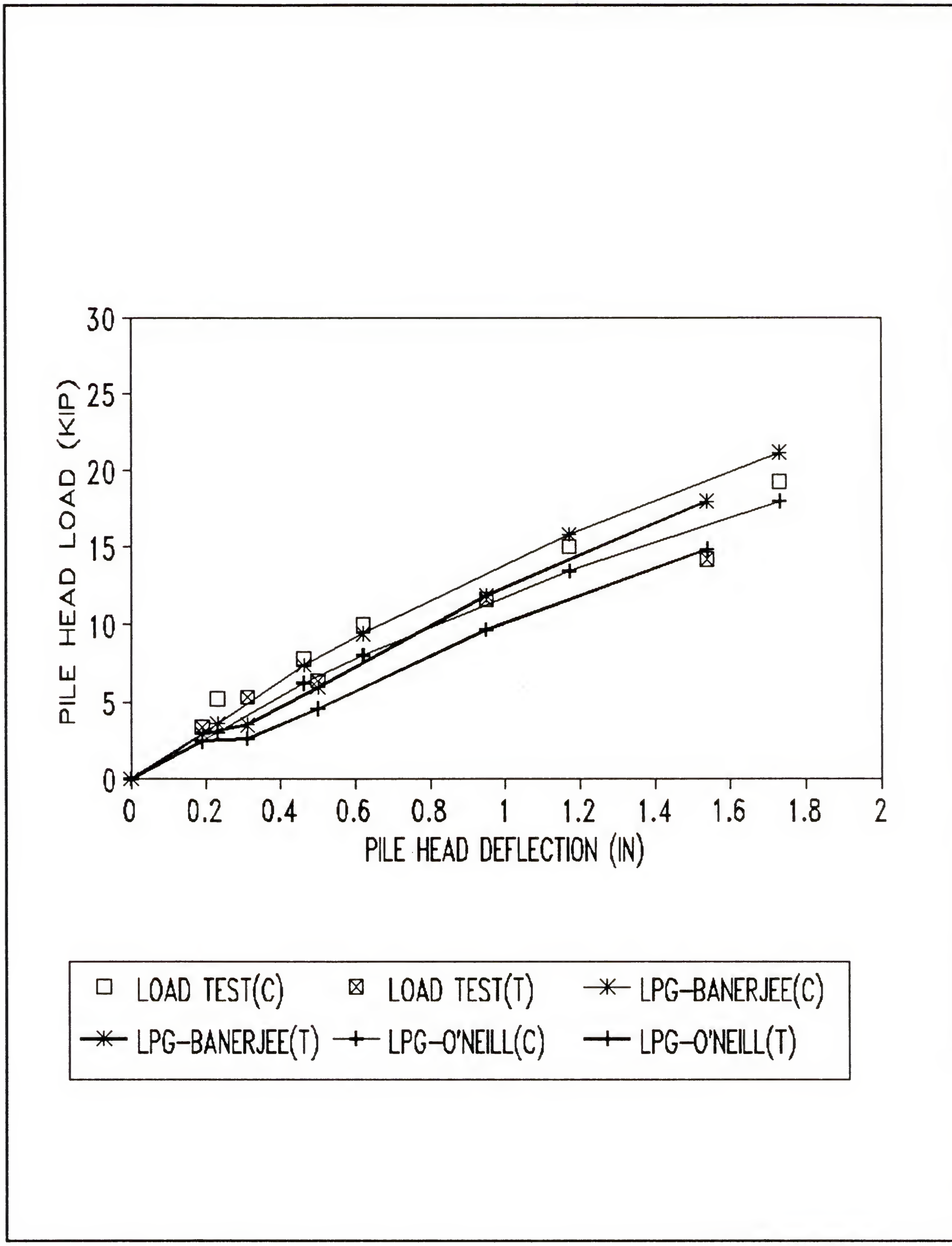


Figure 4.15.--Continued.
(h) Pile #8;

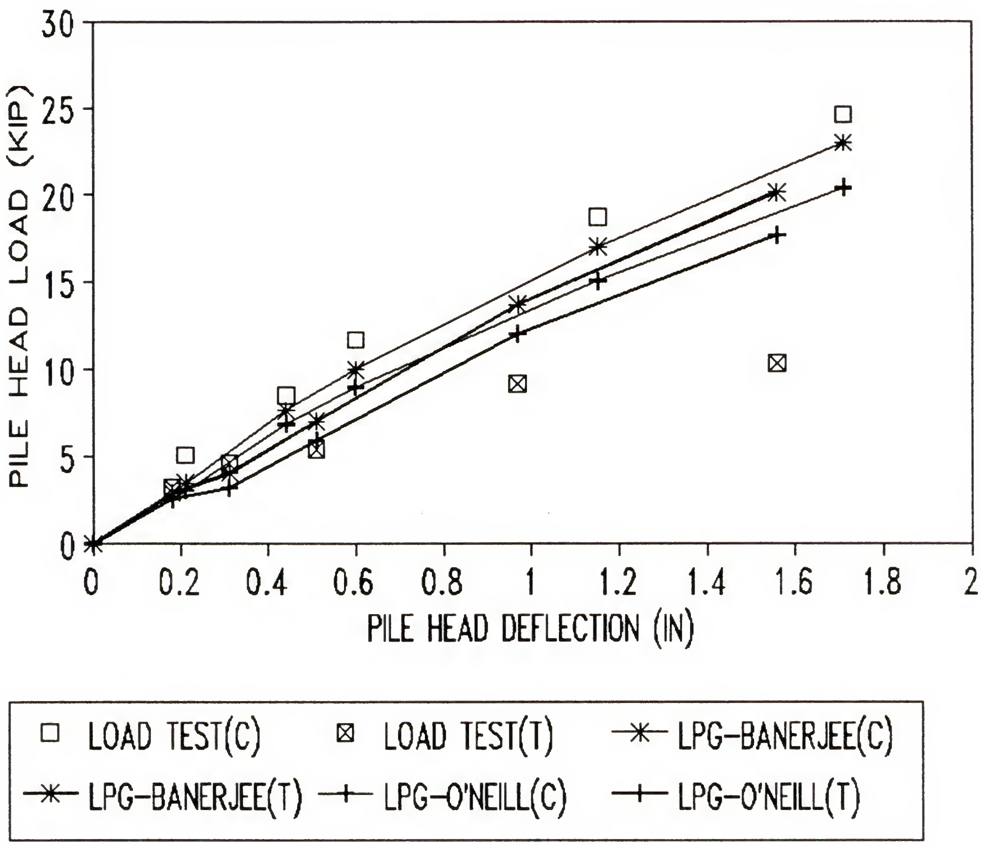


Figure 4.15.--Continued.
(i) Pile #9;

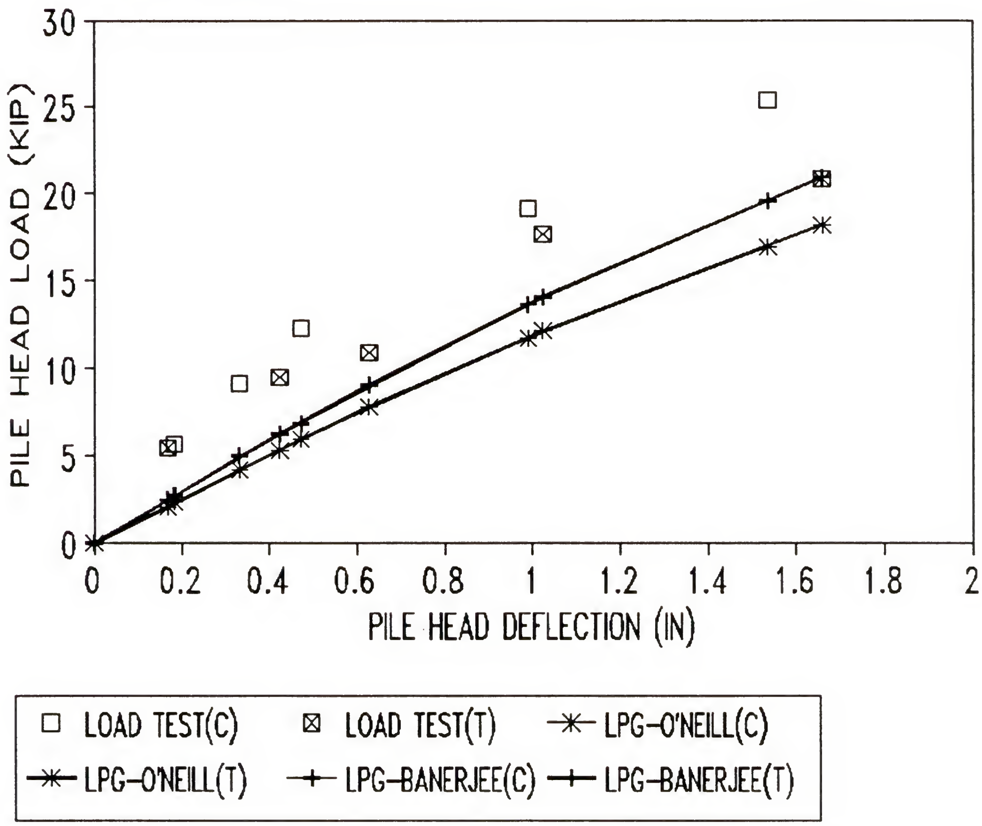


Figure 4.15.--Continued.
(j) Leading Row;

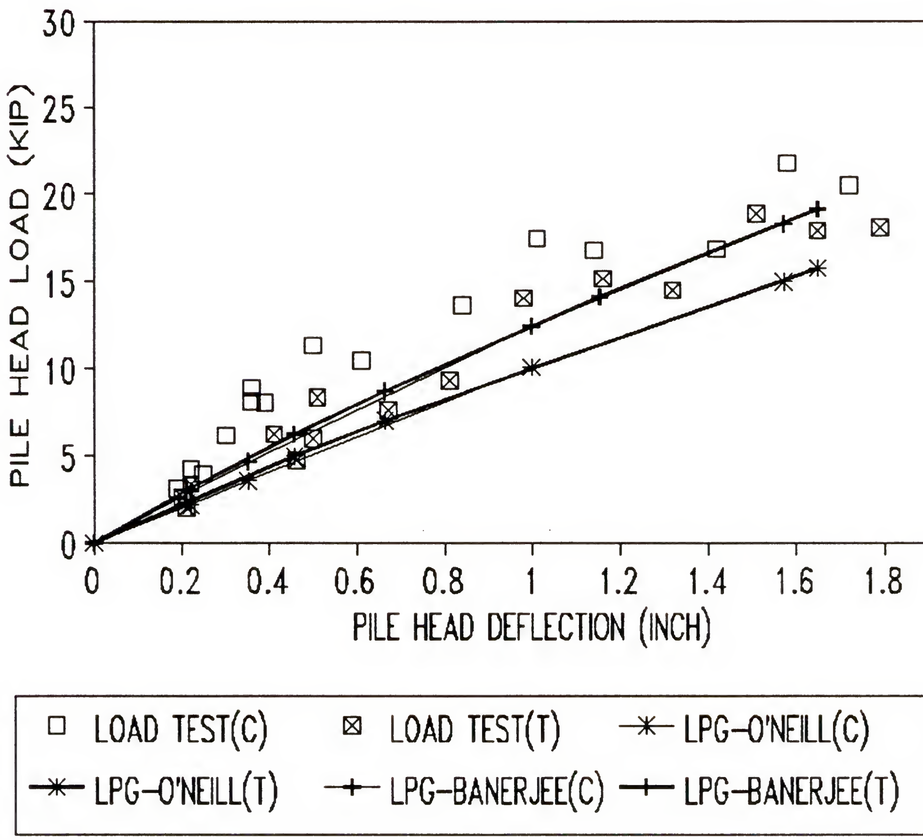


Figure 4.15.--Continued.
(k) Middle Row;

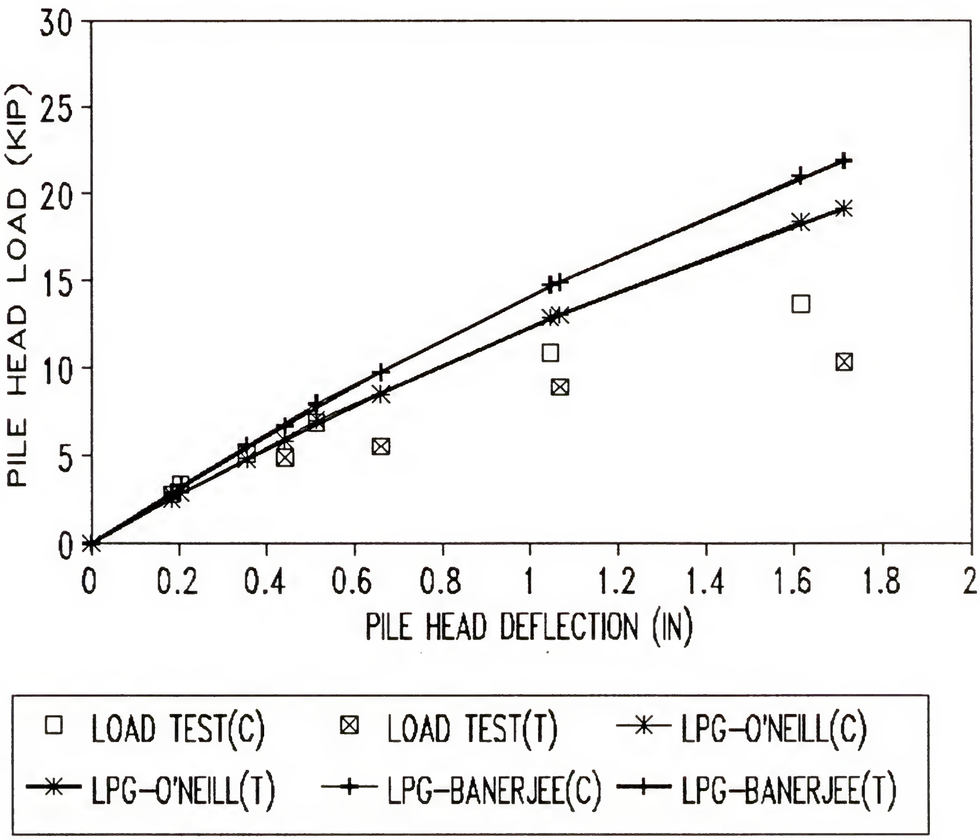


Figure 4.15.--Continued.
(l) Trailing Row;

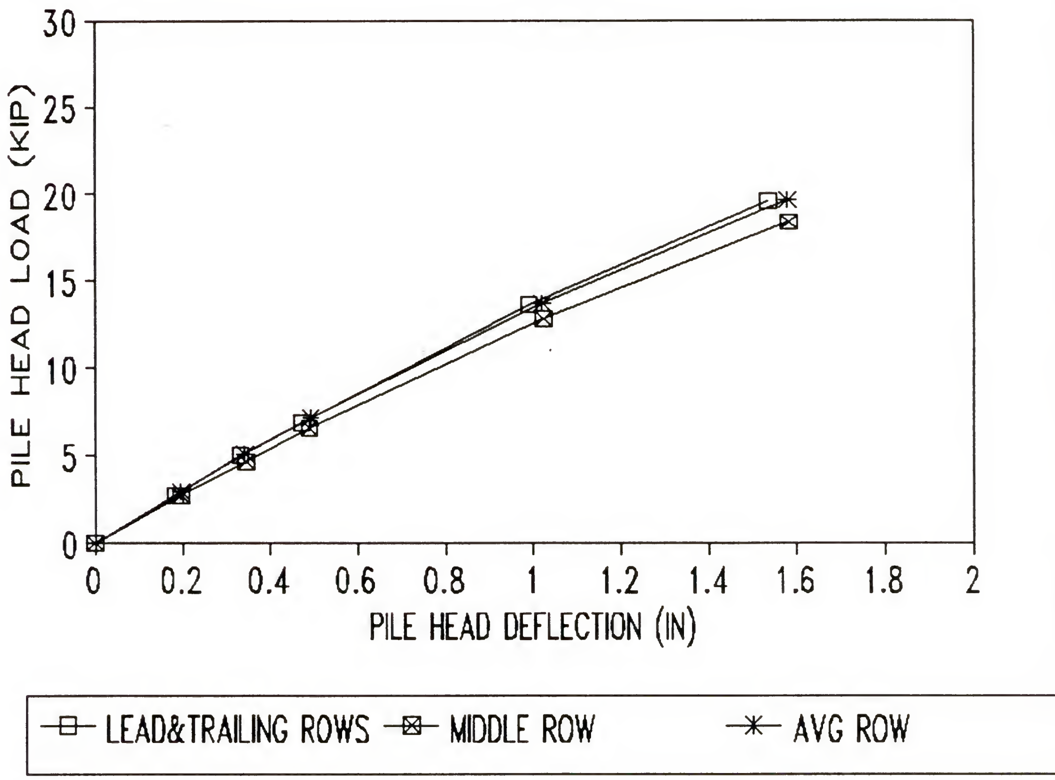


Figure 4.15.--Continued.
(m) Leading, Middle and Trailing Rows and Average Row [as predicted by LPG-Banerjee];

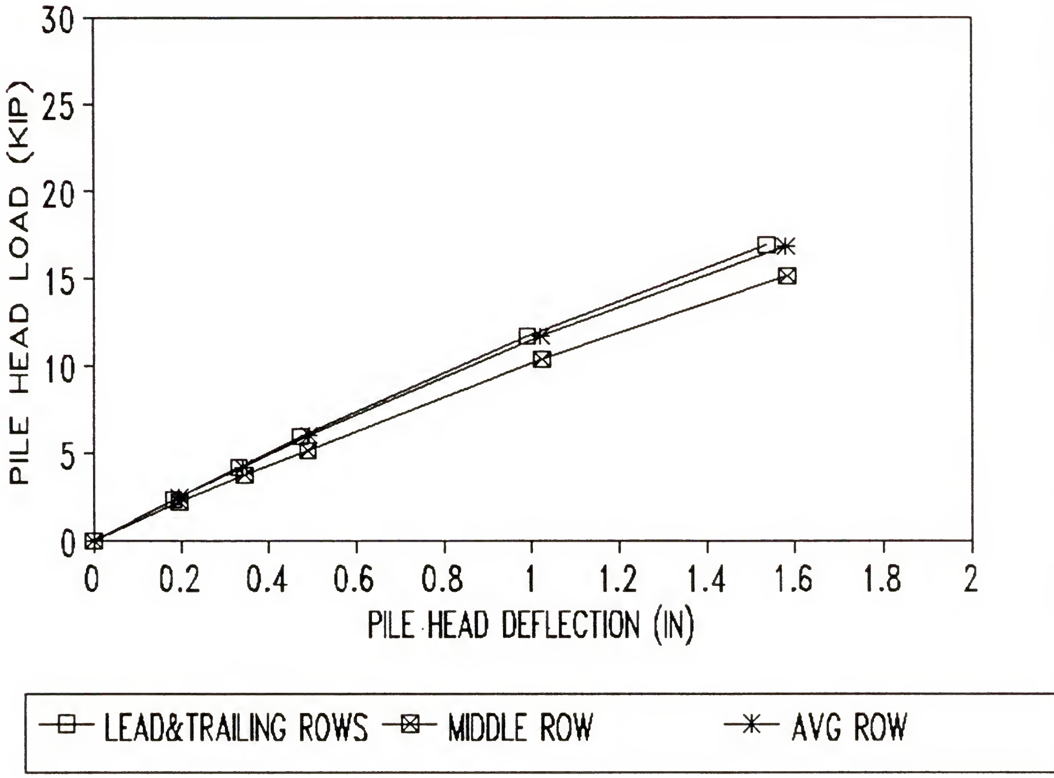


Figure 4.15.--Continued.
(n) Leading, Middle and Trailing Rows and Average Row [as predicted by LPG-O'Neill];

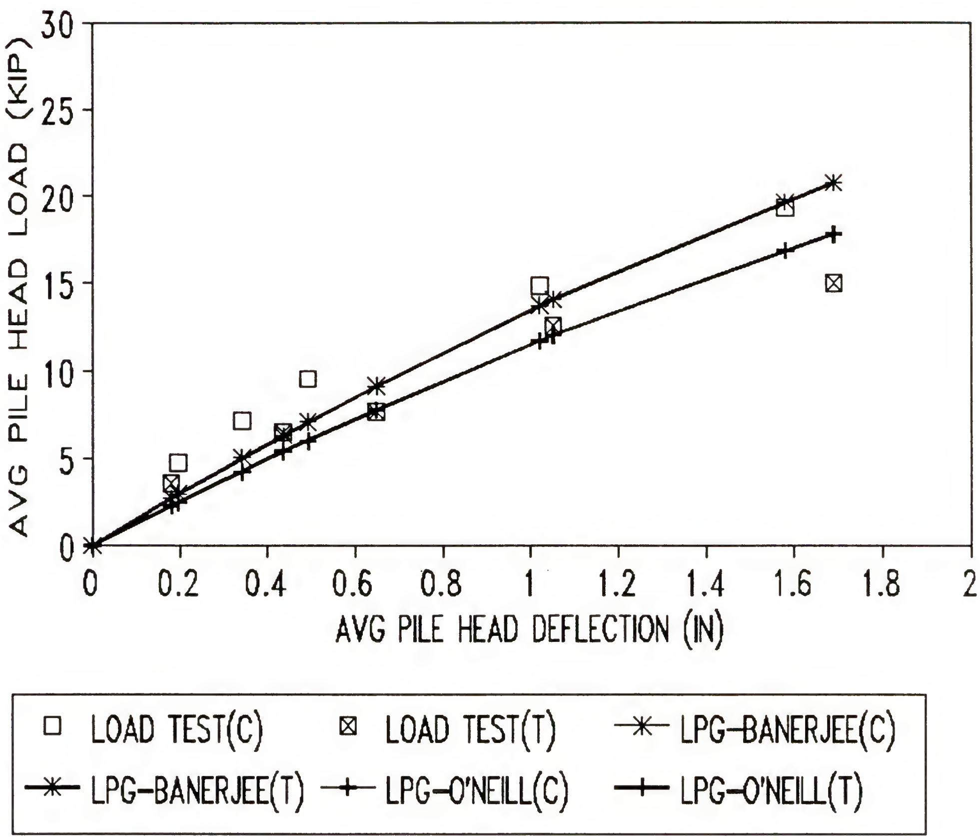


Figure 4.15.--Continued.
(o) Average pile

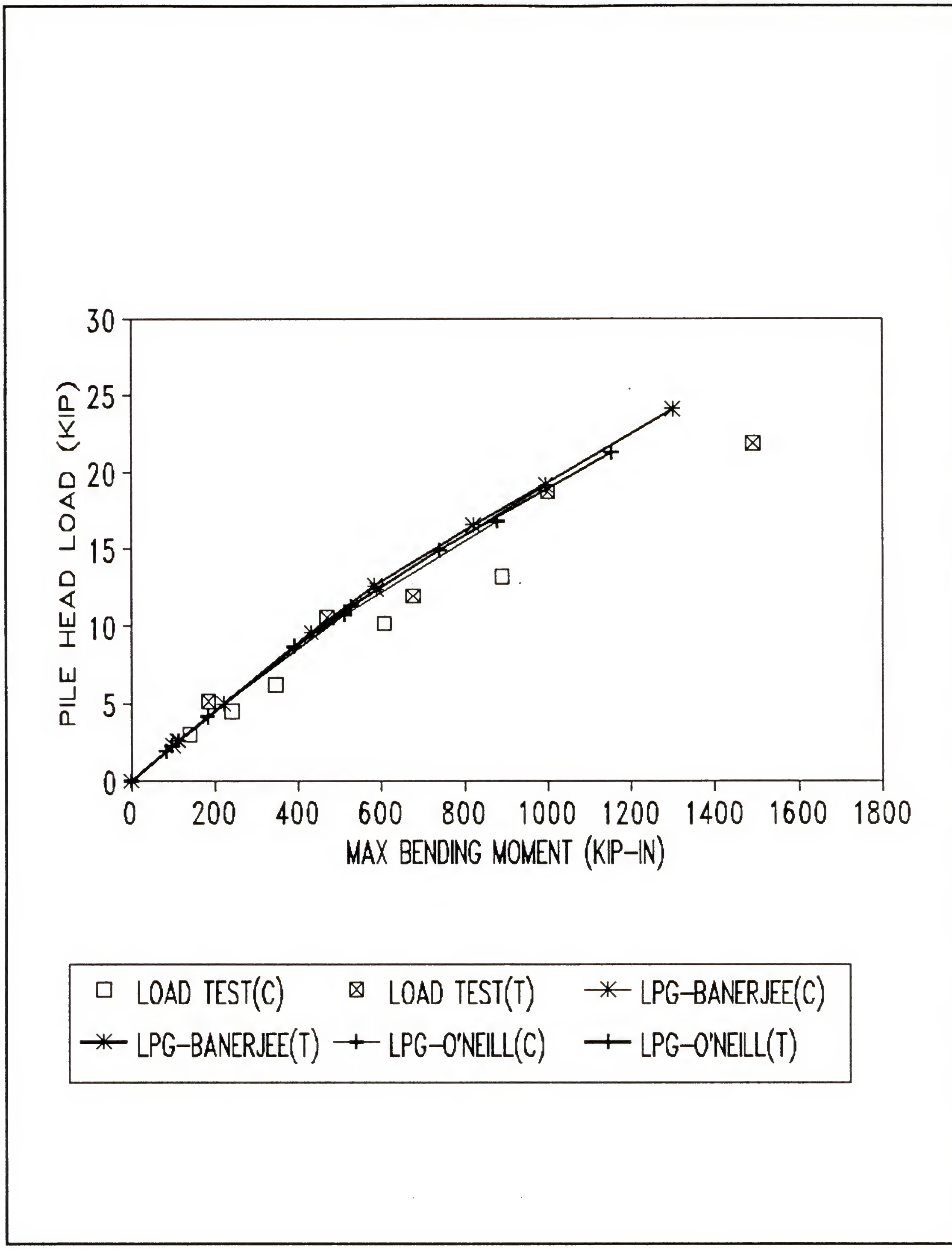


Figure 4.16. Pile-Head Load Vs Maxmimum Bending Moment for the Houston, Texas Pile Group for Cycle #100.
(a) Pile #1;

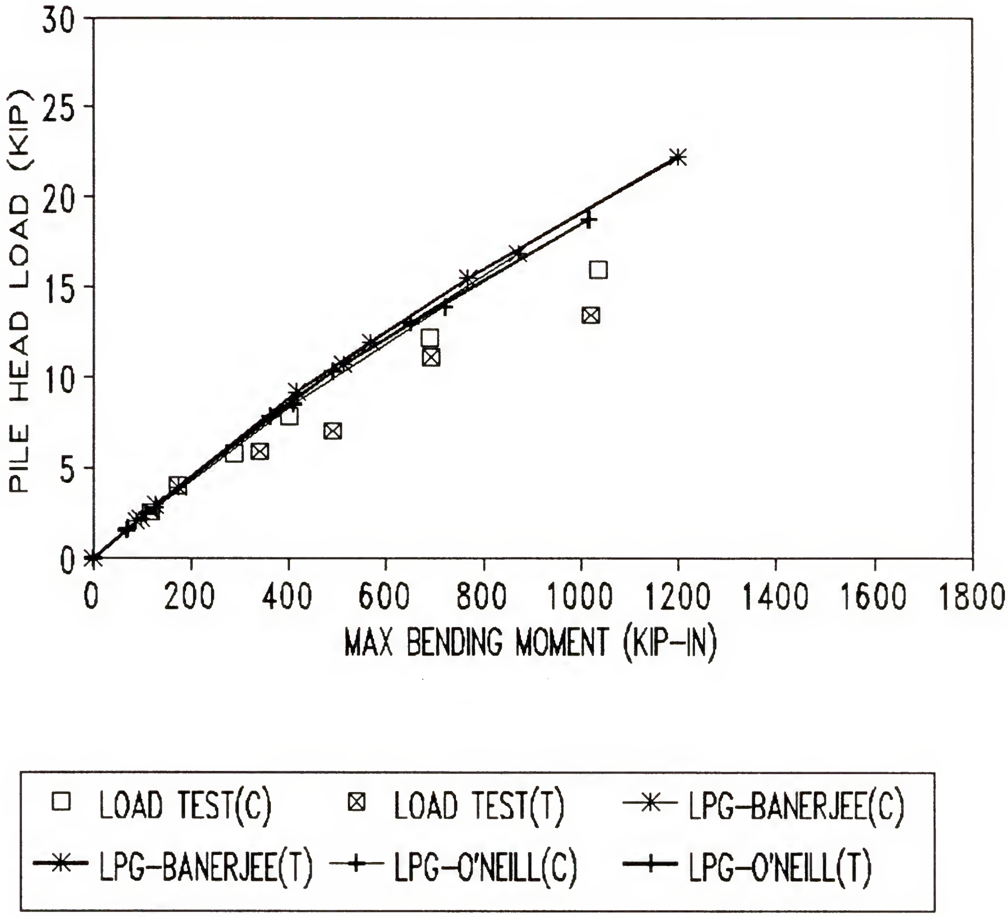


Figure 4.16.--Continued.
(b) Pile #2;

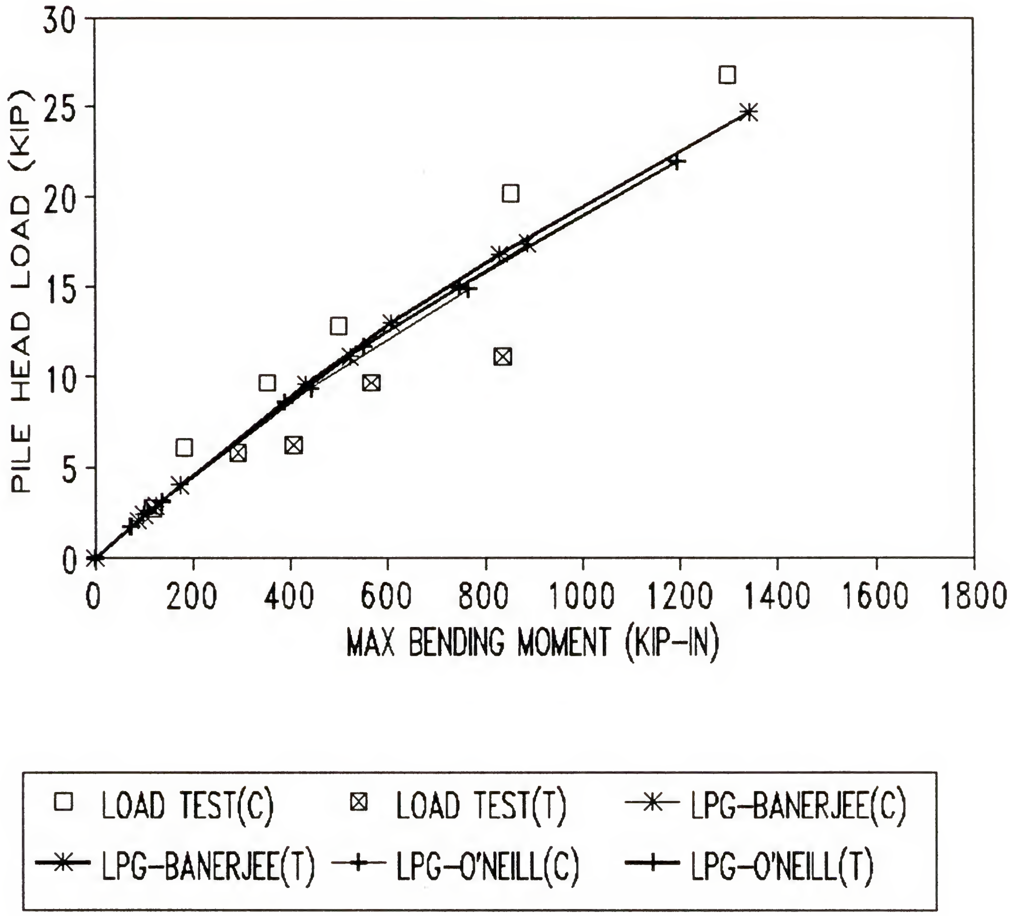


Figure 4.16.--Continued.
(c) Pile #3;

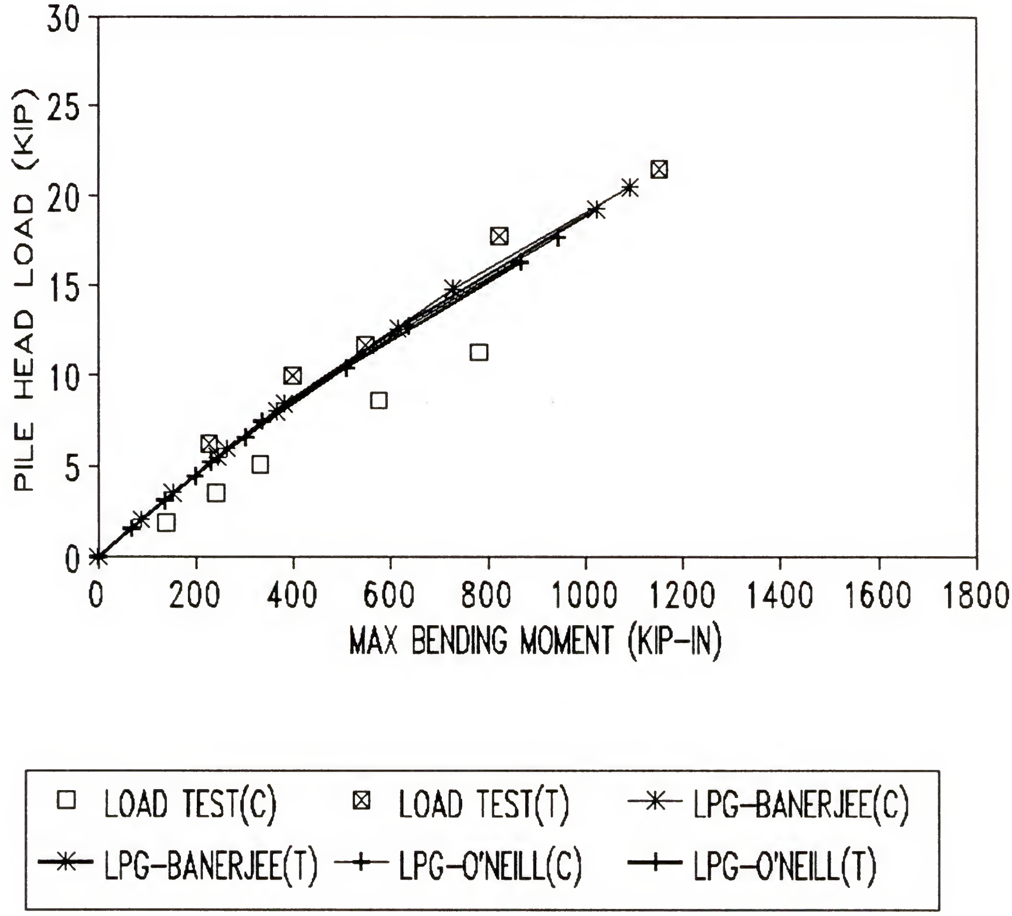


Figure 4.16.--Continued.
(d) Pile #4;

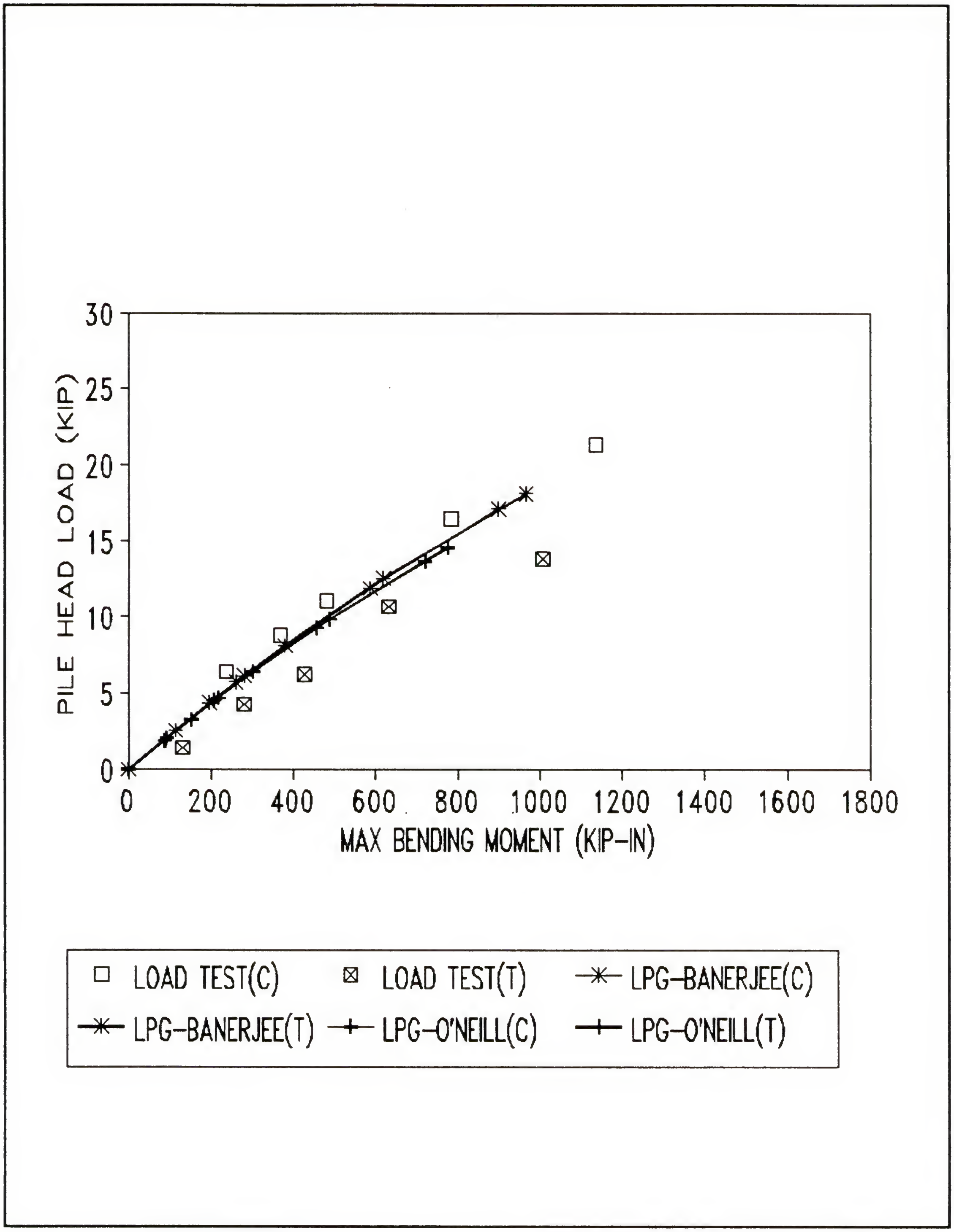


Figure 4.16.--Continued.
(e) Pile #5;

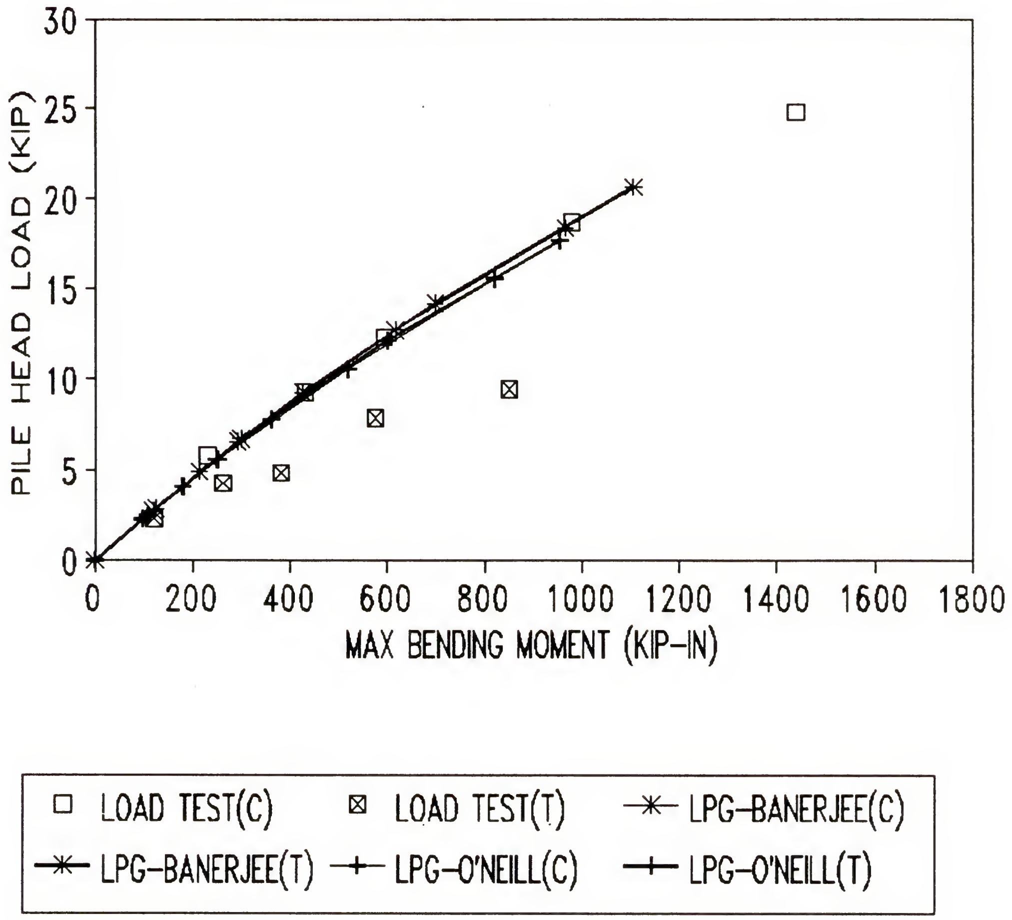


Figure 4.16.--Continued.
(f) Pile #6;

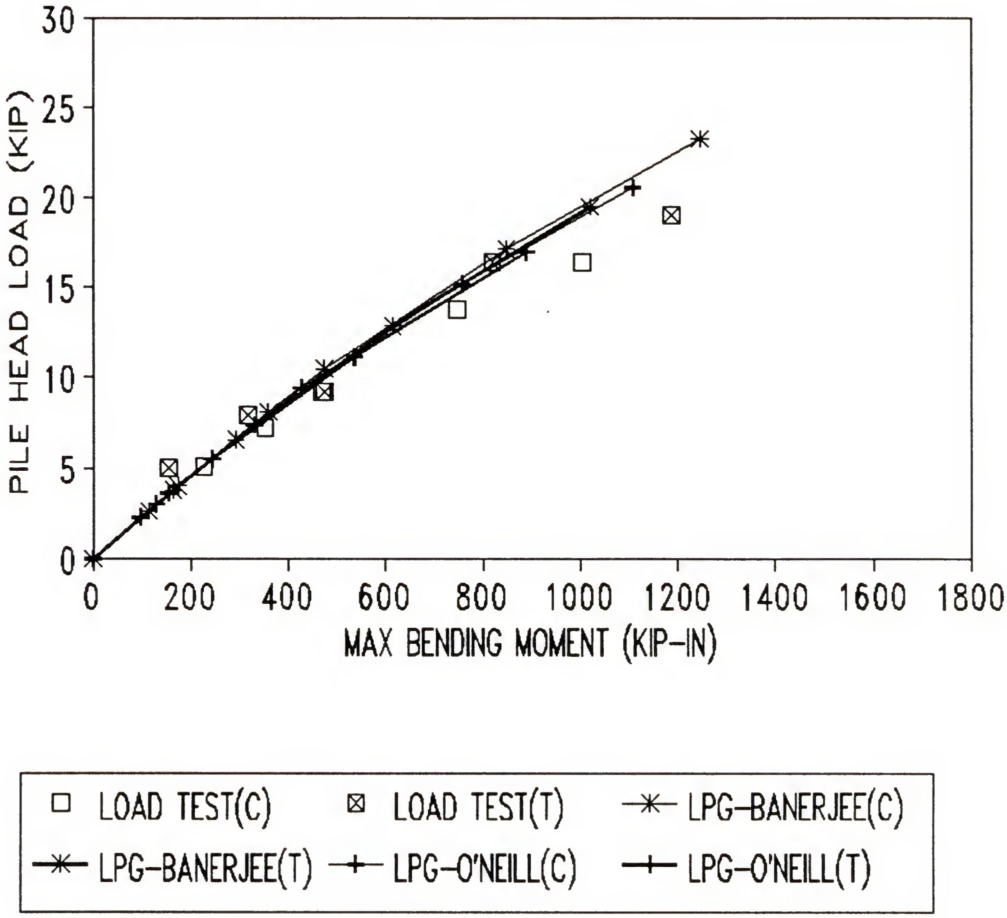


Figure 4.16.--Continued.
(g) Pile #7;

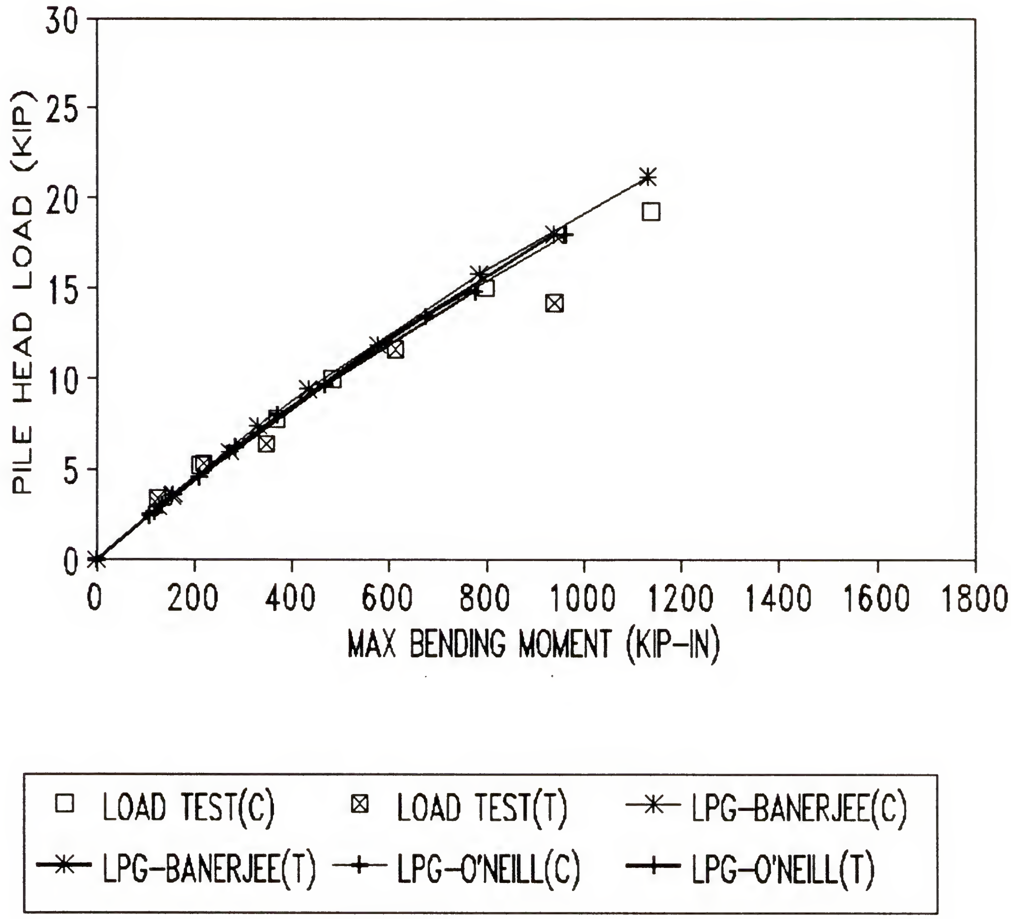


Figure 4.16.--Continued.
(h) Pile #8;

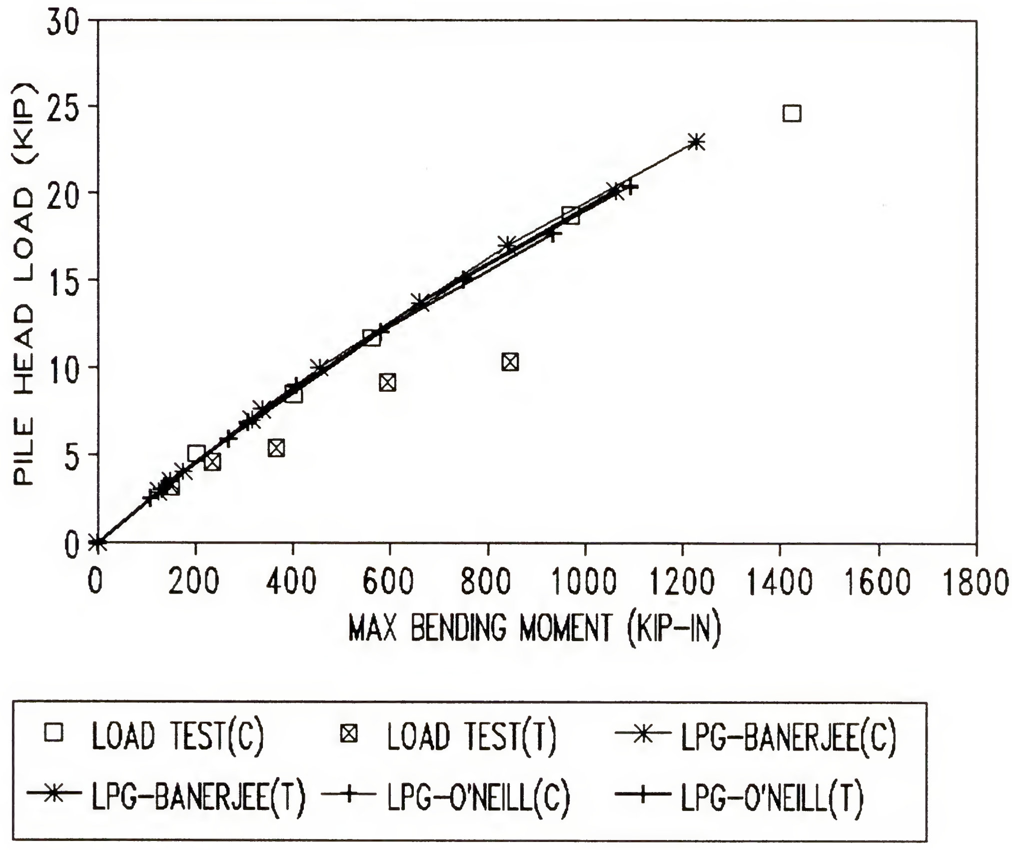


Figure 4.16.--Continued.
(i) Pile #9;

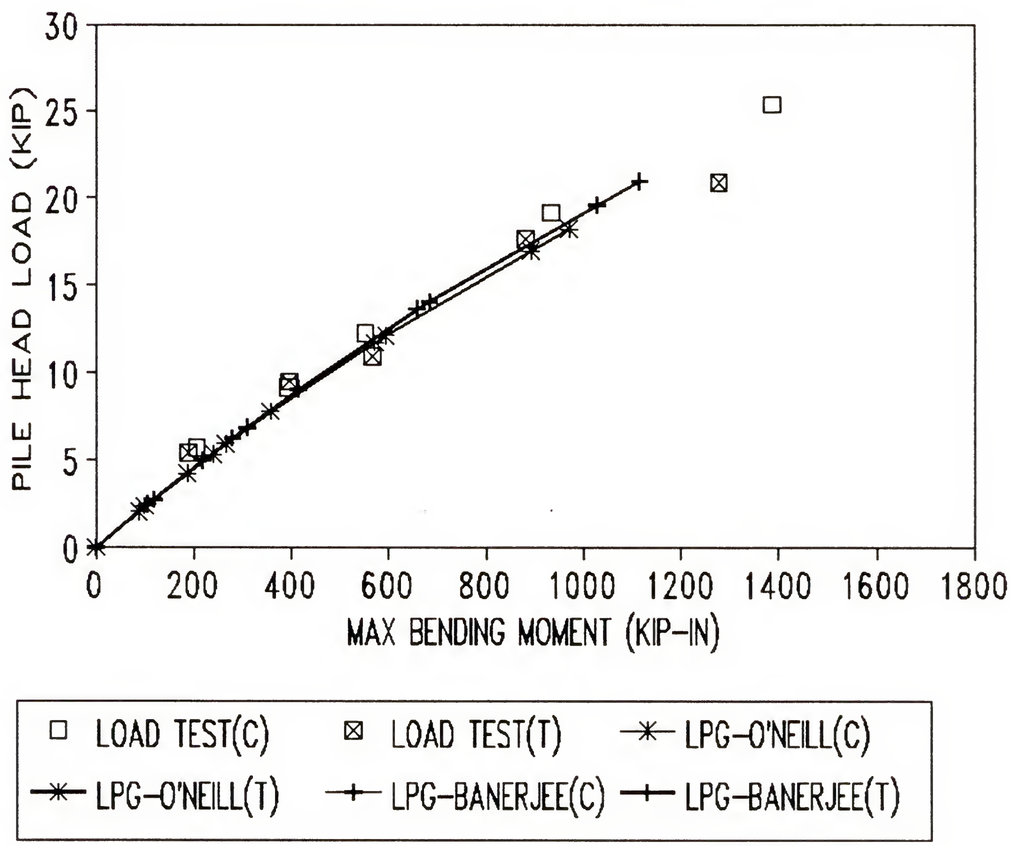


Figure 4.16.--Continued.
(j) Leading Row;

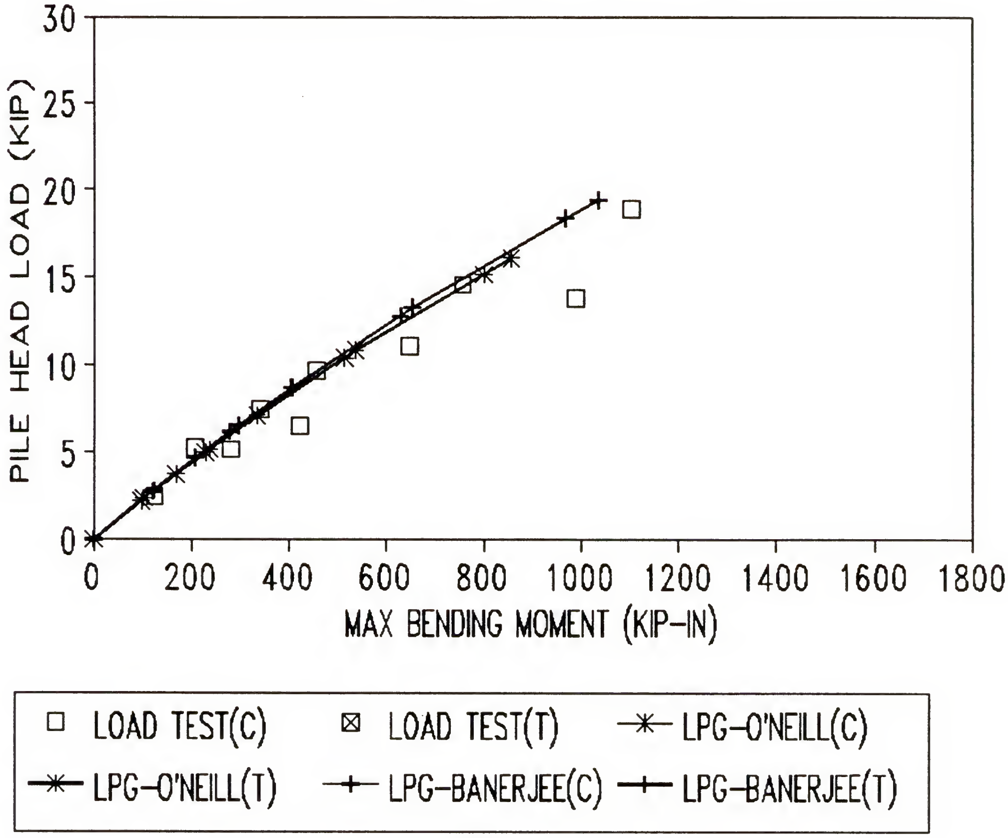


Figure 4.16.--Continued.
(k) Middle Row;

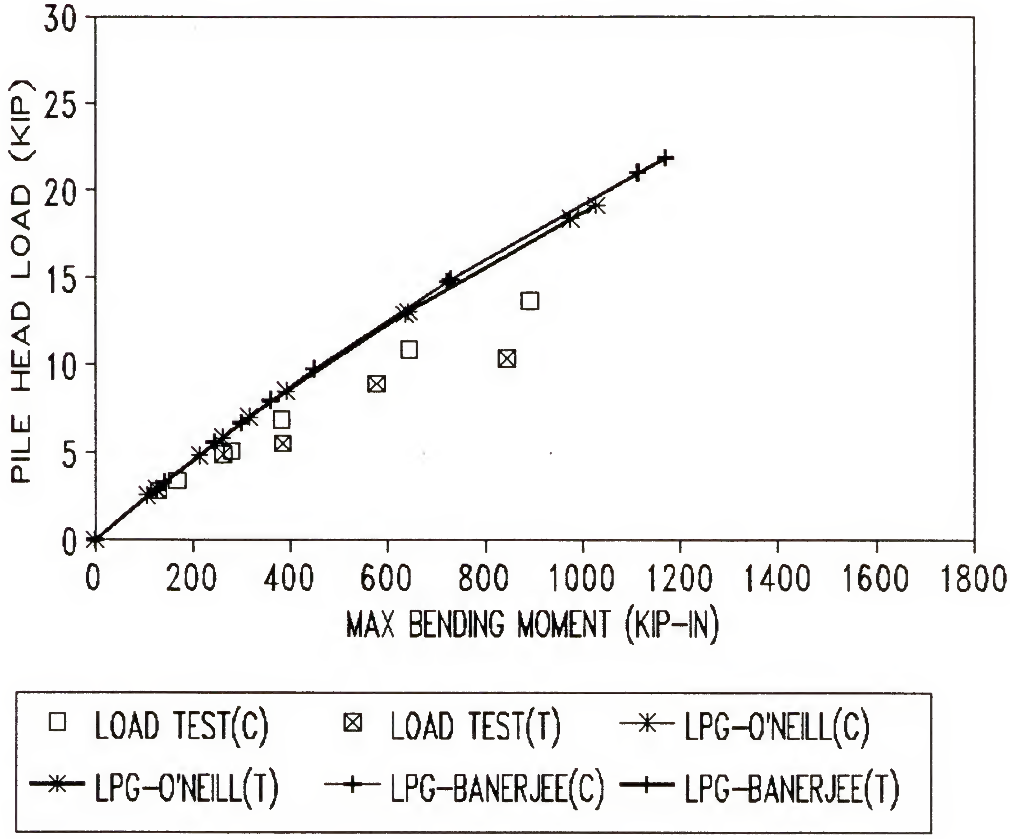


Figure 4.16.--Continued.
(l) Trailing Row;

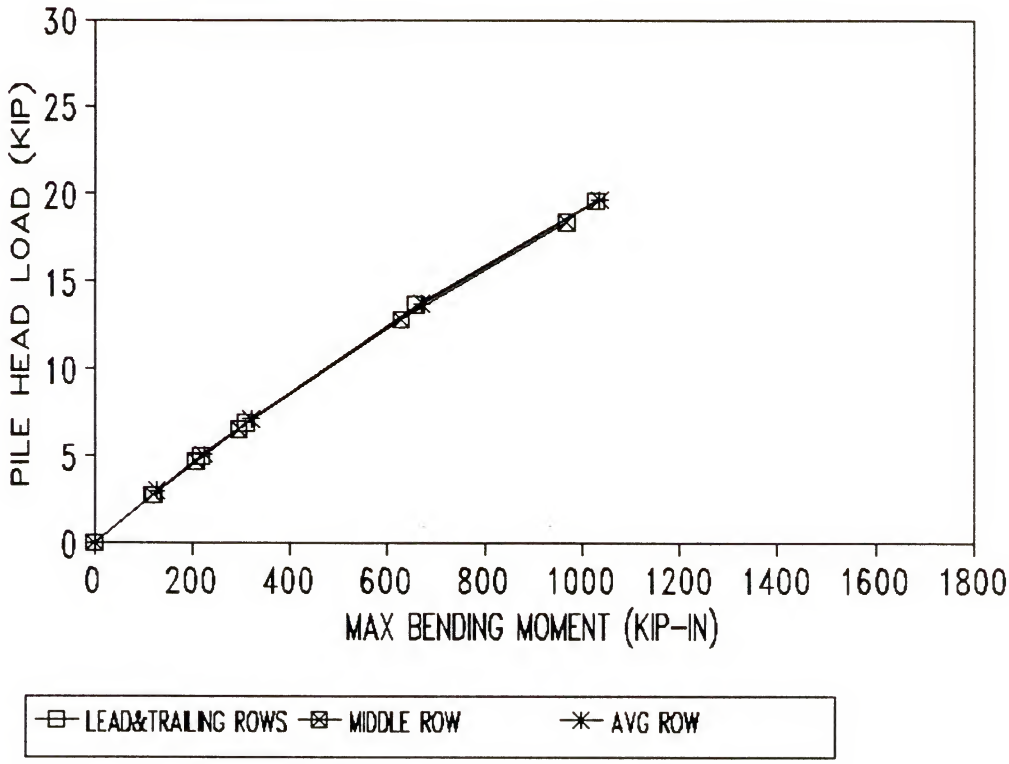


Figure 4.16.--Continued.
(m) Leading, Middle and Trailing Rows and Average Row [as predicted by LPG-Banerjee];

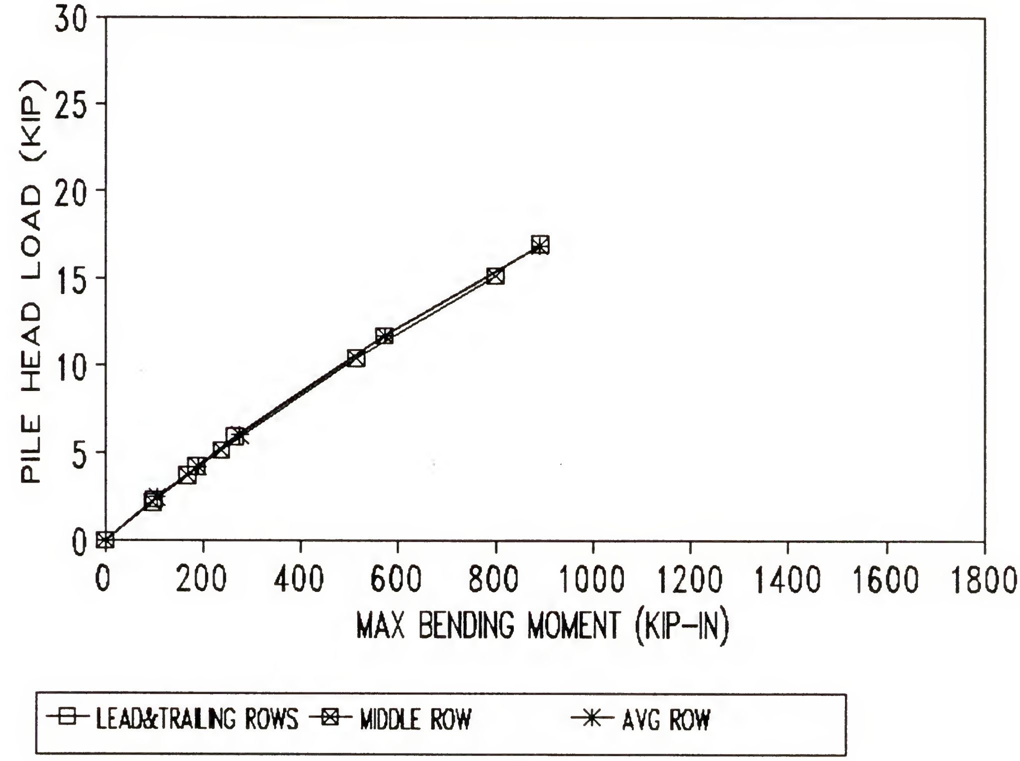


Figure 4.16.--Continued.
(n) Leading, Middle and Trailing Rows and Average Row [as predicted by LPG-O'Neill];

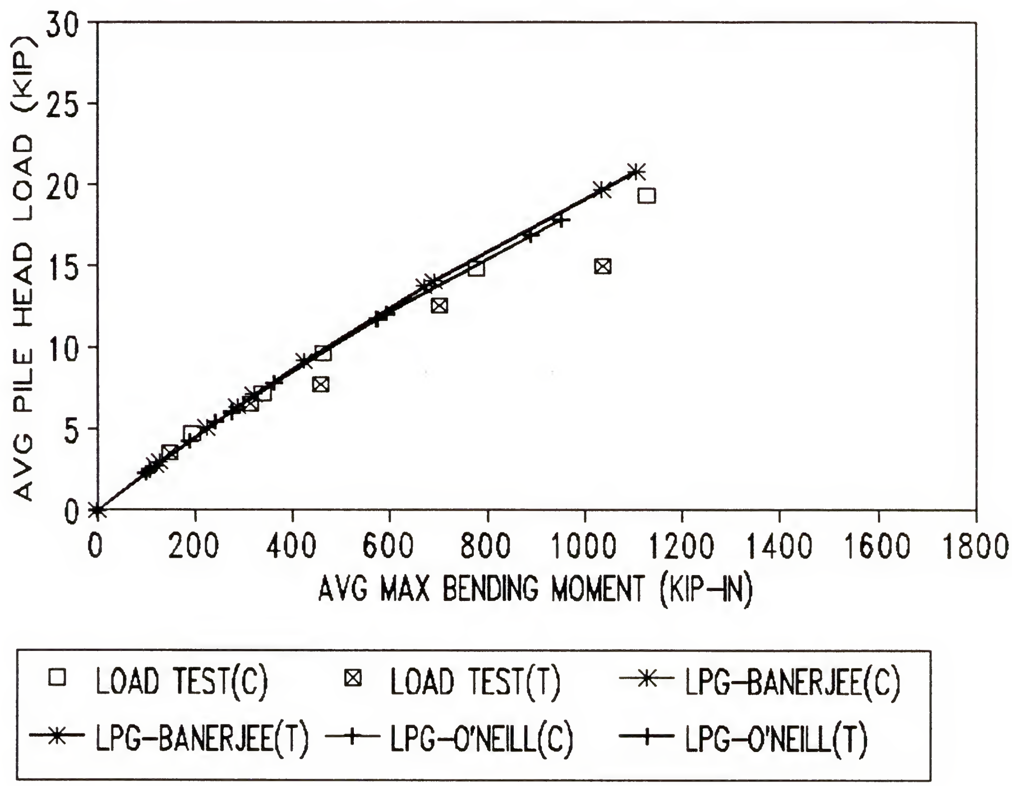


Figure 4.16.--Continued.
(o) Average pile

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this research was to develop a nonlinear FEM computer program (LPG) to model laterally loaded pile groups. From the results obtained using the program, following conclusions and recommendations have been arrived at:

1. The program LPG reproduced elastic solutions for laterally loaded single piles and pile groups fairly well.

2. For a nonlinear or realistic soil, it predicted that lateral load capacity of a single pile is higher than average lateral load capacity of a group pile and the group piles tend to behave like the single pile when spacing between them increases.

3. For a real-world single pile problem, it predicted very good response both for static and cyclic loadings.

4. For a real-world pile group problem, it predicted the response of an average pile in the group very well for both static and cyclic loadings.

5. Numerical value of the input parameter Gs, the shear modulus of the soil had significant influence on the group behavior. So further research like centrifuge model tests is recommended to evaluate Gs for different soils.

For the Houston, Texas pile group (3) analyzed as a model of a typical real-world pile group problem, a value of 842 psi for Gs produced good results and this value was arrived at by using Banerjee and Davies's (1) correlation of Es to Cu. This correlation was also implemented in the method suggested by O'Neill (6) for calculating the p-y curve for a cohesive soil which is used in the program.

6. The field data obtained from the Houston, Texas pile group load test exhibited row-wise load distribution with trailing, middle and leading rows having load capacities in the order of increasing magnitude (3). But the program LPG predicted identical load capacities for the leading and trailing rows. The reason for identical load capacities is the use of Mindlin's elastic flexibilities (13) to calculate far field effect within a pile group. In future, if available, it is recommended to implement nonlinear elastic flexibilities into the program to represent the far field effect. Also, the Mindlin's flexibilities are valid only for a homogeneous elastic half space. To better approximate the far field effect, flexibilities valid for a layered half space, such as suggested by Luco[+], could be used.

[+]Note. Luco, J.E. and Wong, H.L., "Seismic Response of Foundations Embedded in a Layered Half-Space," Earthquake Engineering and Structural Dynamics, Vol. 15, pp. 233-247, 1987.

APPENDIX A
CALCULATION OF INITIAL SLOPES OF NONLINEAR P-Y CURVES

A.1 Sand

$$p = \eta \; A \; p_u \tanh \left[\left(\frac{kz}{A \; \eta \; p_u} \right) \; y \right]$$

$$\frac{dp}{dy} = \eta \; A \; p_u \operatorname{sech}^2 \left[\left(\frac{kz}{A \; \eta \; p_u} \right) \; y \right] \; \frac{k \; z}{\eta \; A \; p_u}$$

$$= k \; z \operatorname{sech}^2 \left[\left(\frac{k \; z}{A \; \eta \; p_u} \right) \; y \right]$$

$$\therefore \quad \frac{dp}{dy} \Big|_{y=0} = k \; z = \text{initial slope of p-y curve for sand.}$$

A.2 Clay

$$p = pu \; 0.5 \; (y/y_c)^{0.387}$$

$$\frac{dp}{dy} = pu \; 0.5 \; 0.387 \; \frac{1}{(y/y_c)^{0.613}} \; \frac{1}{y_c}$$

$$\therefore \quad \frac{dp}{dy} \Big|_{y=0} = \infty = \text{initial slope of p-y curve for clay.}$$

APPENDIX B
USER'S MANUAL FOR LPG-VERSIONS 1 AND 2

B.1 Introduction

LPG (Laterally loaded Pile Group) is a nonlinear FEM program specifically developed for analyzing a laterally loaded pile group. In this program, piles are modeled by 3-D finite beam elements. Pile-soil and pile-soil-pile interaction among the piles and soil within the group is modeled by soil springs. The interaction is assumed to be effected by two types of springs, near-field and far-field soil springs. The near field soil springs are nonlinear and their stiffnesses are obtained from p-y curves (6,10,14). The far-field soil springs are linear and their stiffnesses are obtained from Mindlin's flexibility equations (13). Axial loads are transferred to the soil through the axial soil springs attached to the tips of the piles. Since the soil is nonlinear, the solution of the system will require many iterations.

The program is written in FORTRAN77 and is very portable. It is recommended to run the program in main frame computers such as IBM 3090 and VAX or micro systems such as Sun or Sony.

B.2 Input Conventions

(1) Any consistent units can be used.

(2) For square piles use:

dia= $4/\pi$ * width of pile

(3) Following default values may be used for the maximum # of iterations for nonlinear soil analysis (MAXITER) and the tolerance on displacements (TOLER) for convergence:

MAXITER = 50

TOLER = 10^{-3}

(4) (a) Following typical values may be used for the Poisson's ratio RNU for soils:

RNU = 0.3 for sand

= 0.5 for clay

A spatial average, for the values of RNU at seventeen nodes where p-y curves (section B.2.6) are input, may be used for soils consisting of both sand and clay.

(b) Regarding the shear modulus GM of soils, currently there is not sufficient data in literature and further research like centrifuge testing needs to be done. Until more information is available, approximately GM may be obtained at any depth z from the following relationships:

GM = 0.5 * k * z / (1+RNU) for sand

= 50 * Cu / (1+RNU) for clay

where k = soil modulus (F/L^3)

z = depth below ground surface (L)

Cu = undrained shear strength (F/L^2)

A spatial average, for the values of GM at seventeen nodes where p-y curves (section B.2.6) are input, should be used for any soil profile.

(5) For defining a p-y curve, use p-y data either for sand (ϕ,k,γ,0,0,0) or clay (0,0,0,Cu,ϵ50,ϵ100). For sand, use SPT to find ϕ (Figure 3.5) and ϕ to find k (F/L^3) (Figure 3.6). To define a linear p-y curve using the option KSOIL = 0 or 1, use p-y data in the format (0,k,0,0,0,0).

(6) Total 17 p-y curves, one for each node of a pile must be defined. For pile group with

(a) free standing height (Z) > 0 [Figure B.1 (a)],

Node #1 is at the top of the pile, node #2 is on the ground surface and node #17 is at the tip of the pile. Nodes #2-17 are equally spaced inside the soil at an interval given below:

$$\Delta l = (\text{total length of pile} - Z) / 15$$

<u>THE P-Y CURVE DEFINED FOR NODE #1 IS IGNORED BUT IT IS NECESSARY TO INPUT DATA.</u>

(b) free standing height (Z) = 0 [Figure B.1 (b)],

Node #1 is at the top of the pile and also on the ground surface and node #17 is at the tip of the pile. Nodes 1-17 are equally spaced inside the soil at an interval given below:

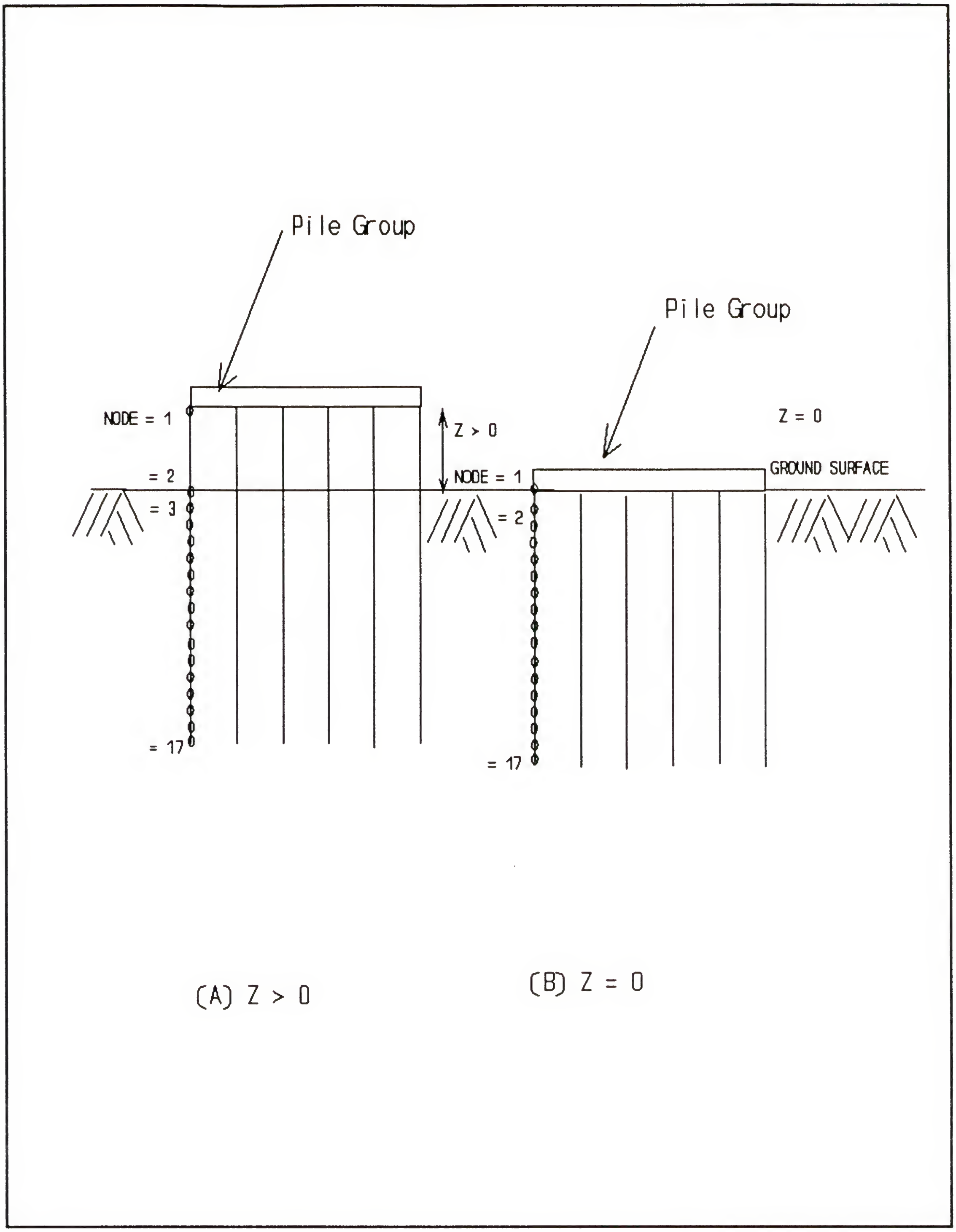


Figure B.1. P-Y Data Preparation.

Δl = total length of pile / 16

B.3 Input Data Format

LINE #1 (NAME):

Input

1. Title (maximum 70 characters) (CHARACTER)

LINE #2 (UNITS):

Input

1. List of units like FT,KIPS,RAD or INCH,LBS,RAD or any consistent set of units (maximum 70 characters) (CHARACTER)

LINE #3 (KFLAG):

Input

1. 0 for complete print out
   1 for summary print out

LINE #4 (TPL,E,RINER,AREA,DIA):

Input

1. Total pile length (REAL,*†)
2. Youngs modulus of pile (REAL,*)
3. Moment of inertia of pile (REAL,*)
4. Area of cross-section of pile (REAL,*)
5. Dia of pile (REAL,*)

LINE #5 (Z,KCYC):

Input

1. Length of pile above ground surface

---

†Note. An asterisk means free formatted input in FORTRAN language.

(It can also be equal to zero) (REAL,*)

2. 0 for static loading (INTEGER,*)

   1 for cyclic loading (INTEGER,*)

LINE #6 (NPILE)/(NPILE,NPA):

Input

1. Total number of piles in the group
2. None for PROFILE version of LPG

   Number of asymmetric piles for LU version of LPG

LINE #7 (MAXITER,TOLER):

Input

1. Maximum # of iterations for the nonlinear soil analysis (INTEGER,*)
2. Tolerance on displacements for the nonlinear soil analysis (REAL,*)

LINE #8 (KSOIL,GM,RNU):

Input

1. 0 for linear p-y curves with Es*†† constant with depth;

   1 for linear p-y curves with Es* linearly varying with depth;

   2 for non-linear p-y curves
2. Shear Modulus of the soil (REAL,*)
3. Poisson's ratio of the soil (REAL,*)

LINE #9 (TSTIF):

Input

---

††<u>Note</u>. The secant modulus of soil reaction (lb/in^2 or N/m^2) is defined as Es* = p/y.

1. Tip spring stiffness (REAL,*)

LINE #10:26 (total of 17 lines, one for each p - y curve PHI,RK,GAMMAD,C,E50,E100)

Input

1. Angle of internal friction (REAL,*)
2. Soil modulus k[†††] (REAL,*)
3. Effective unit weight of the soil (REAL,*)
4. Undrained shear strength (REAL,*)
5. Major principal strain @ 50 % maximum deviator stress in a UU triaxial compression test (REAL,*)
6. Major principal strain @ failure in a UU triaxial compression test (REAL,*)

(NOTE: EACH LINE CORRESPONDS TO EACH OF 17 NODES OF A PILE MEMBER)

LINE #27:(27+NPILE) (Total of NPILE lines, each for one pile PGEOX, PGEOY)

Input

1. X coordinate of pile
2. Y coordinate of pile

LINE #(27+NPILE):(27+NPILE+1) (NPS)

Input

None for PROFILE version and

[†††]<u>Note</u>. For this value, input
(a) modulus of lateral subgrade reaction (lb/in^3 or N/m^3) for KSOIL=2
(b) the value of Es^* (lb/in^2 or N/m^2) for KSOIL=0
(c) the slope (lb/in^3 or N/m^3) of Es^* Vs Depth curve for KSOIL=1

NPA pile symmetry numbers for LU version (The asymmetric piles must be defined a priori to invoke symmetry option in LU version.)

LINE #(27+NPILE+1):(27+NPILE+2) (KDZ,KDX,KDY,KBX,KBY) Input

1. 0 for force boundary condition for pile top displacements in Z direction

   1 for displacement boundary condition for pile top displacements in Z direction

2. 0 for force boundary condition for pile top displacements in X direction

   1 for displacement boundary condition for pile top displacements in X direction

3. 0 for force boundary condition for pile top displacements in Y direction

   1 for displacement boundary condition for pile top displacements in Y direction

4. 0 for force boundary condition for pile top bending moment about X axis

   1 for displacement boundary condition pile top bending moment about X axis

5. 0 for force boundary condition for pile top bending moment about Y axis

   1 for displacement boundary condition pile top bending moment about Y axis

LINE #(27+NPILE+1):(27+NPILE+2+NPILE) (Total NPILE lines, one for each pile)

Input

1. Force in Z direction at pile top for KDZ = 0

   Displacement in Z direction at pile top for KDZ = 1
2. Force in Z direction at pile top for KDX = 0

   Displacement in X direction at pile top for KDX = 1
3. Force in Z direction at pile top for KDY = 0

   Displacement in Y direction at pile top for KDY = 1
4. Bending moment about X axis at pile top for KBX = 0

   Rotation about X axis at pile top for KBX = 1
5. Bending moment about Y axis at pile top for KBY = 0

   Rotation about Y axis at pile top for KBY = 1

LINE #(27+NPILE+1):(27+NPILE+2+NPILE+1) (NDINC)

Input

1. Number of displacement/force increments

APPENDIX C
FORTRAN CODE OF PROGRAM LPG-VERSION 1 (PROFILE)

```
C      MAIN PROGRAM - LPG VERSION 1(PROFILE)
C                   - PROGRAMMED BY SHANMUGRAJ SUBRAMANIAN
C                   - MAY 1992
C*******************************************************
C      THIS PROGRAM CALCULATES THE LOAD-DEFLECTION BEHAVIOR
C      OF A PILE GROUP SUBJECTED TO LATERAL LOADS USING FEM
C      TECHNIQUE
C
C*********************************************************
C      -  CHANGE THE FOLLOWING LINES TO ALTER THE SIZE AND
C         PRECISION OF COMPUTER ANALYSIS OF THE PILE GROUP
C
       PARAMETER( MTOT = 550000,
     +            IPR  = 2     )
C*********************************************************
C      DEACTIVATE THE FOLLOWING LINES  FOR SINGLE PRECISION
C      CALCULATIONS
       DOUBLE PRECISION TPL,E,RINER,AREA,DIA,X,ELENP,GM,RNU,
     +TOLER,STEP,ERRDIS,ERRMAX,GSE,CL,TSTIF
C*********************************************************
       CHARACTER*70 NAME,UNITS
       COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
       COMMON/SOIL/GM,RNU
       COMMON/OUTPUT/NUO1,NUO2
       COMMON/POINT/MFIRST,MLAST,IPRCN
       COMMON/TIT/NPILE,MAXITN,TOLER,NDINC,TSTIF,KFLG,UNITS
       COMMON/BIG/A(MTOT)
       DATA ZERO/0.0/
       NUI=7
       NUO1=8
       NUO2=9
       NUO3=10
       IPRCN=IPR
       MFIRST=1
       MLAST=MTOT
       CL=ZERO
       CALL OPEN(NUI,NUO1,NUO2,NUO3)
       WRITE(*,*)' .................READING DATA'
       READ(NUI,2)NAME
       READ(NUI,2)UNITS
       READ(NUI,*)KFLG
       READ(NUI,*)TPL,E,RINER,AREA,DIA
       READ(NUI,*)X,KCYC
       READ(NUI,*)NPILE
       READ(NUI,*)MAXITN,TOLER
       READ(NUI,*)KSOIL,GM,RNU
       READ(NUI,*)TSTIF
       NNP=17*NPILE
       NNPS=16*NPILE
       IF(X.EQ.ZERO)NNPS=17*NPILE
       NEQ=5*NNP
```

```
 NPEL=16*NPILE
 NFLXS=32*NPILE
 IF(X.EQ.ZERO)NFLXS=34*NPILE
 WRITE(NUO1,21)NAME
 WRITE(NUO1,3)
 CALL PRNTIT(NUO1)
 MPPY=MPOINT(17,6,IPR)
 CALL MREAD(A(MPPY),17,6,NUI)
 IF(KSOIL.EQ.0)THEN
    ASSIGN 51 TO NFMT
 ELSE
    ASSIGN 5 TO NFMT
 ENDIF
 NAME='PY CURVES DATA:'
 WRITE(NUO1,NFMT)NAME
 CALL MPRINT(A(MPPY),17,6,NUO1,17,6,3)
 MPPGEO=MPOINT(NPILE,2,IPR)
 CALL MREAD(A(MPPGEO),NPILE,2,NUI)
 NAME='PILE GEOMETRY:'
 WRITE(NUO1,6)NAME
 CALL MPRINT(A(MPPGEO),NPILE,2,NUO1,NPILE,2,3)
 MPPCOO=MPOINT(NNP,3,IPR)
 CALL PILCOR(A(MPPCOO),A(MPPGEO),NPILE,NNP)
 READ(NUI,*)KTZ,KTX,KTY,KRX,KRY
 WRITE(NUO1,198)KTZ,KTX,KTY,KRX,KRY
 MPCDIS=MPOINT(NPILE,5,2)
 CALL MREAD(A(MPCDIS),NPILE,5,NUI)
 WRITE(NUO1,221)
 CALL MPRINT(A(MPCDIS),NPILE,5,NUO1,NPILE,5,3)
 READ(NUI,*)NDINC
 WRITE(NUO1,222)NDINC
 NFT=(NFLXS+1)*NFLXS/2
 MPFPSP=MPOINT(NFT,0,IPR)
 MPNAF=MPOINT(NFLXS,0,1)
 CALL FLEXNA(A(MPNAF),NFLXS)
 CALL FLEX(A(MPPCOO),A(MPFPSP),A(MPNAF),NNP,NFLXS,NFT)
 CALL MATW(A(MPFPSP),NFT,1,NUO3)
 NLDOF=NFLXS
 MPLM=MPOINT(NFLXS,0,1)
 CALL LMPSP(A(MPLM),NEQ,NLDOF)
 MPNAG=MPOINT(NEQ,0,1)
 CALL GLBNA(A(MPLM),A(MPNAG),NGT,NFLXS,NEQ,NPILE)
 MPGLK=MPOINT(NGT,0,IPR)
 CALL NULVEC(A(MPGLK),NGT)
 MPEKPT=MPOINT(10,10,IPR)
 MPEKPB=MPOINT(10,10,IPR)
 MPLM1=MPOINT(10,0,1)
 NLDOF=10
 CALL ELSTFP(A(MPEKPB),NLDOF,1)
 IF(X.EQ.ZERO)THEN
     CALL COPYM(A(MPEKPB),A(MPEKPT),NLDOF,NLDOF)
 ELSE
     CALL ELSTFP(A(MPEKPT),NLDOF,0)
 ENDIF
 NNL=(NPILE-1)*17+1
 DO 30 NSUM=1,NNL,17
 DO 30 NN=NSUM,(NSUM+15)
 CALL LMPEL(A(MPLM1),NN,NLDOF)
 IF(MOD(NN,17).EQ.1)THEN
     CALL ADDSTF1(A(MPGLK),A(MPEKPT),A(MPNAG),A(MPLM1),
+NGT,NLDOF,NEQ)
 ELSE
     CALL ADDSTF1(A(MPGLK),A(MPEKPB),A(MPNAG),A(MPLM1),
+NGT,NLDOF,NEQ)
```

```
      ENDIF
30    CONTINUE
      MPIFOR=MPOINT(5*NPILE,0,1)
      MPFOR=MPOINT(5*NPILE,0,IPR)
      CALL BOUND(A(MPIFOR),A(MPFOR),A(MPCDIS),A(MPGLK),
     +A(MPNAG),NGT,NEQ,NPILE,KTZ,KTX,KTY,KRX,KRY)
      CALL TIP(A(MPGLK),A(MPNAG),TSTIF,NGT,NEQ)
      WRITE(NUO1,3)
      CALL MATW(A(MPGLK),NGT,1,NUO3)
      MPSPSP=MPOINT(NFLXS,NFLXS,IPR)
      WRITE(*,*)' ::::::MAX # OF INCREMENT(S) = ',NDINC
      WRITE(*,*)' ::::::MAX # OF ITERATION(S) = ',MAXITN
      CALL INISTF(A(MPFPSP),A(MPPY),A(MPPCOO),A(MPSPSP),
     +A(MPNAF),NNP,NFLXS,NFT)
      NLDOF=NFLXS
      CALL ADDSTF1(A(MPGLK),A(MPSPSP),A(MPNAG),A(MPLM),
     +NGT,NLDOF,NEQ)
      MPEXTF=MPOINT(NEQ,0,IPR)
      MPINTF=MPOINT(NEQ,0,IPR)
      MPDISP=MPOINT(NEQ,0,IPR)
      MPODIS=MPOINT(NEQ,0,IPR)
      MPPSPF=MPOINT(NFLXS,0,IPR)
      MPPF=MPOINT(NPEL,10,IPR)
      MPSPRF=MPOINT(NFLXS,0,IPR)
      MPSF=MPOINT(NPILE,5,IPR)
      WRITE(*,78)MTOT,(MFIRST-1),(MTOT-MFIRST+1)
      WRITE(NUO1,78)MTOT,(MFIRST-1),(MTOT-MFIRST+1)
      WRITE(NUO1,3)
      WRITE(NUO1,61)GSE
      IF(KFLG.EQ.0)THEN
         NAME='COORDINATES OF PILE NODES:'
         WRITE(NUO1,7)NAME
         CALL MPRINT(A(MPPCOO),NNP,3,NUO1,17,3,3)
      ENDIF
      DO 50 IN=1,NDINC
      WRITE(*,*)'INCREMENT# = ',IN
      STEP=DBLE(IN)
      CALL NULVEC(A(MPEXTF),NEQ)
      CALL NULVEC(A(MPODIS),NEQ)
      CALL EXTFOR(STEP,A(MPIFOR),A(MPFOR),A(MPEXTF),
     +NPILE,NEQ)
      ICON=0
      DO 60 IT=1,MAXITN
      WRITE(*,*)' ITERATION # = ',IT
      CALL COPYM(A(MPEXTF),A(MPDISP),NEQ,1)
      WRITE(*,*)' SOLVING THE SYSTEM EQUATIONS'
      CALL SUBSOL(A(MPGLK),A(MPDISP),A(MPNAG),NEQ,NEQ,1,4)
      ERRDIS=ERRMAX(A(MPODIS),A(MPDISP),NEQ)
      IF(IT.NE.1.AND.ERRDIS.LE.TOLER)ICON=1
      IF(ICON.EQ.1)THEN
            REWIND NUO3
            CALL MATR(A(MPFPSP),NFT,1,NUO3)
            CALL MATR(A(MPGLK),NGT,1,NUO3)
            CALL SECSTF(A(MPDISP),A(MPFPSP),A(MPSPSP),
     +A(MPPY),A(MPNAF),A(MPPCOO),A(MPLM),A(MPSPRF),NNP,NNPS,
     +NFLXS,NEQ,NFT)
            CALL ADDSTF1(A(MPGLK),A(MPSPSP),A(MPNAG),A(MPLM),
     +NGT,NLDOF,NEQ)
            CALL OBFOR(A(MPGLK),A(MPDISP),A(MPINTF),
     +A(MPEXTF),A(MPNAG),NEQ,NGT)
            WRITE(NUO1,75)
            WRITE(NUO1,76)IN,IT,ERRDIS
            WRITE(NUO1,75)
            CALL PRINTF(A(MPDISP),A(MPLM),A(MPPY),A(MPPCOO),
```

```
     +A(MPINTF),A(MPSPSP),A(MPEKPT),A(MPEKPB),A(MPPSPF),
     +A(MPPF),A(MPSPRF),A(MPSF),NPEL,NEQ,NNP,NNPS,NPILE,
     +NFLXS,KFLG)
            GO TO 50
      ELSE
            IF(IT.EQ.MAXITN)THEN
               WRITE(NUO1,75)
               WRITE(*,77)IN,IT,ERRDIS
               WRITE(NUO1,77)IN,IT,ERRDIS
               WRITE(NUO1,75)
               STOP
            ELSE
               REWIND NUO3
               CALL MATR(A(MPFPSP),NFT,1,NUO3)
               CALL MATR(A(MPGLK),NGT,1,NUO3)
               CALL SECSTF(A(MPDISP),A(MPFPSP),A(MPSPSP),
     +A(MPPY),A(MPNAF),A(MPPCOO),A(MPLM),A(MPSPRF),
     +NNP,NNPS,NFLXS,NEQ,NFT)
               CALL ADDSTF1(A(MPGLK),A(MPSPSP),A(MPNAG),
     +A(MPLM),NGT,NLDOF,NEQ)
               CALL COPYM(A(MPDISP),A(MPODIS),NEQ,1)
            ENDIF
      ENDIF
60    CONTINUE
50    CONTINUE
2     FORMAT(A)
21    FORMAT(1X,A)
3     FORMAT(
     +1X,'*******************************************',
     +'*****************************',/)
5     FORMAT(/,1X,A,/,T18,'PHI',T30,'K',T35,'GAMMA`',
     +T49,'CU',T58,'E50',T67,'E100',/,T16,'(DEG)',
     +T24,'(F/L^3)',T34,'(F/L^3)',T44,
     +'(F/L^2)',T56,'(L/L)',T66,'(L/L)'/)
51    FORMAT(/,1X,A,/,T18,'PHI',T30,'K',T35,
     +'GAMMA`',T49,'CU',T58,'E50',T67,'E100',/,T16,
     +'(DEG)',T24,'(F/L^2)',T34,'(F/L^3)',T44,
     +'(F/L^2)',T56,'(L/L)',T66,'(L/L)'/)
6     FORMAT(/,1X,A,/,T6,'PILE#',T20,'X',T30,'Y')
61    FORMAT(/,
     +T22,'::::     OUTPUT    ::::',//,
     +T5,'GROUND SURFACE ELEVATION   = ',E10.3,1X,'(L)')
7     FORMAT(/,1X,A,/,T7,'PILE',T20,'X',T30,'Y',T40,'Z',/,
     +T6,'NODE#')
76    FORMAT(T5,'THE SOLUTION CONVERGED FOR:',/,
     +T5,'DISPLACEMENT/FORCE INCREMENT #   = ',I10,/,
     +T5,'                    ITERATION #   = ',I10,/,
     +T5,'MAX  DEFLECTION  ERROR            = ',E10.3,1X,
     +'(L)',/)
77    FORMAT(
     +T5,'THE SOLUTION COULD NOT CONVERGE FOR:',/,
     +T5,'DISPLACEMENT/FORCE INCREMENT #   = ',I10,/,
     +T5,'MAX  ITERATION                #   = ',I10,/,
     +T5,'MAX  DEFLECTION  ERROR            =',E10.3,
     +1X,'(L)')
78    FORMAT(
     +1X,'TOTAL # OF MEMORY UNITS         = ',I10,/,
     +1X,'# OF MEMORY UNITS USED BY LPG = ',I10,/,
     +1X,'# OF MEMORY UNITS FREE          = ',I10,/)
75    FORMAT(/,
     +1X,'____________________________________________'
     +,'_______________________',/,1X,'_______'
     +,'__________________________________________'
     +,'_______________')
```

```
221   FORMAT(1X,'CAP LOADS/DISPLACEMENTS:',/,
     +T6,'PILE#',T14,'FZZ/DZZ',T24,'FXX/DXX',T34,'FYY/DYY',
     +T44,'MXX/RXX',T54,'MYY/RYY')
222   FORMAT(1X,'# OF LOAD INCREMENT(S) = ',I10,/)
198   FORMAT(1X,'BOUNDARY CONDITIONS CODE:',/,
     +1X,'  FOR TRANSLATION IN Z DIRECTION = ',I2,/,
     +1X,'                     X           = ',I2,/,
     +1X,'                     Y           = ',I2,/,
     +1X,'  FOR ROTATION ABOUT X AXIS      = ',I2,/
     +1X,'                     Y AXIS      = ',I2,/)
      END
C-----------------------------------------------------------
       SUBROUTINE ADDSTF1(GLK,S,NAG,LM,NGT,ND,NEQ)
C
C      THIS ROUTINE ADDS THE ELEMENT STIFFNESS MATRIX TO THE
C      GLBOBAL STIFFNESS MATRIX
C***********************************************************
C      DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C      CALCULATIONS
       IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C**********************************************************
       DIMENSION GLK(NGT),NAG(NEQ),S(ND,ND),LM(ND)
       DO 200 I=1,ND
       N=LM(I)
       DO 100  J=I,ND
       M=LM(J)
       SS=S(I,J)
       IF(M.GT.N)THEN
           LOC=NAG(M)+N-M
       ELSE
           LOC=NAG(N)+M-N
       ENDIF
       GLK(LOC)=GLK(LOC)+SS
100    CONTINUE
200    CONTINUE
       RETURN
       END
C-----------------------------------------------------------
      SUBROUTINE BOUND(IFOR,FOR,CDIS,STRK,NA,NGT,NEQ,NPILE,
     +KTZ,KTX,KTY,KRX,KRY)
C
C     THIS ROUTINE INCORPORATES BOUNDARY CONDITIONS TO THE
C     TOP OF PILES - ->KTZ,KTX,KTY,KRX,KRY = 0 MEANS FORCE
C     BOUNDARY CONDITION AND = 1 MEANS DISPLACEMENT BOUNDARY
C     CONDITION
C***********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      COMMON/POINT/MFIRST,MLAST,IPRCN
      DIMENSION STRK(NGT),NA(NEQ),IFOR(5*NPILE),
     +FOR(5*NPILE),CDIS(NPILE,5)
      EPB=0.D0
      DO 5 I=1,NGT
      DUM=STRK(I)
      IF(EPB.LT.DUM)EPB=DUM
5     CONTINUE
      EPB=1.D3*EPB
      K=0
      DO 10 I=1,NEQ
      IF(MOD(I,85).EQ.1)THEN
         K=K+1
         K1=(K-1)*5+1
```

```
         IFOR(K1)=I
         IF(KTZ.EQ.0)THEN
            FOR(K1)=CDIS(K,1)
         ELSE
            IPOI=NA(I)
            STRK(IPOI)=STRK(IPOI)+EPB
            FOR(K1)=STRK(IPOI)*CDIS(K,1)
         ENDIF
         K1=(K-1)*5+2
         IFOR(K1)=I+1
         IF(KTX.EQ.0)THEN
            FOR(K1)=CDIS(K,2)
         ELSE
            IPOI=NA(I+1)
            STRK(IPOI)=STRK(IPOI)+EPB
            FOR(K1)=STRK(IPOI)*CDIS(K,2)
         ENDIF
         K1=(K-1)*5+3
         IFOR(K1)=I+2
         IF(KTY.EQ.0)THEN
            FOR(K1)=CDIS(K,3)
         ELSE
            IPOI=NA(I+2)
            STRK(IPOI)=STRK(IPOI)+EPB
            FOR(K1)=STRK(IPOI)*CDIS(K,3)
         ENDIF
         K1=(K-1)*5+4
         IFOR(K1)=I+3
         IF(KRX.EQ.0)THEN
            FOR(K1)=CDIS(K,4)
         ELSE
            IPOI=NA(I+3)
            STRK(IPOI)=STRK(IPOI)+EPB
            FOR(K1)=STRK(IPOI)*CDIS(K,4)
         ENDIF
         K1=(K-1)*5+5
         IFOR(K1)=I+4
         IF(KRY.EQ.0)THEN
            FOR(K1)=CDIS(K,5)
         ELSE
            IPOI=NA(I+4)
            STRK(IPOI)=STRK(IPOI)+EPB
            FOR(K1)=STRK(IPOI)*CDIS(K,5)
         ENDIF
      ENDIF
10    CONTINUE
      RETURN
      END
C-----------------------------------------------------------
      SUBROUTINE DOTP(A,B,S,N)
C
C     THIS ROUTINE CALCULATES THE DOT PRODUCT OF TWO VECTORS
C     'A' AND 'B'
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      DIMENSION A(N),B(N)
      S=0.0D0
      DO 100 I=1,N
  100 S=S+A(I)*B(I)
      RETURN
      END
```

```
C-------------------------------------------------------------
      SUBROUTINE EXTFOR(STEP,IFOR,FOR,EXTF,NPILE,NEQ)
C
C     THIS ROUTINE CALCULATES THE EXTERNAL FORCES APPLIED
C     TO THE PILE GROUP SYSTEM
C
C*************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C*************************************************************
      DIMENSION IFOR(5*NPILE),FOR(5*NPILE),EXTF(NEQ)
      IMAX=5*NPILE
      DO 10 I=1,IMAX
      II=IFOR(I)
      EXTF(II)=FOR(I)*STEP
10    CONTINUE
      RETURN
      END
C-------------------------------------------------------------
      SUBROUTINE FLEX(PCOOR,FLPSP,NAF,NNP,NFLXS,NFT)
C
C     THIS ROUTINE CALCULTES PILE-SOIL-PILE FLEXIBILITY BY
C     MINDLIN FLEXIBILITY EQNS FOR  POINT FORCES APPLIED AT
C     A POINT INSIDE AN ELASTIC CONTINUUM IN X AND Y
C     DIRECTIONS
C*************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C*************************************************************
      COMMON/SOIL/GM,RNU
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DIMENSION PCOOR(NNP,3),FLPSP(NFT),NAF(NFLXS)
      DATA PI,ZERO,ONE,TWO,THREE,FOUR,RN16,EN5
     +/3.1415927,0.0,1.0,2.0,3.0,4.0,16.0,0.00001/
      C1=ONE/(RN16*PI*GM*(ONE-RNU))
      C2=THREE-FOUR*RNU
      C3=FOUR*(ONE-RNU)*(ONE-TWO*RNU)
      NJ=0
      DO 10 J=1,NNP
      IF(X.NE.ZERO.AND.MOD(J,17).EQ.1)GO TO 10
      NJ=NJ+1
      NJ1=(NJ-1)*2+1
      NJ2=(NJ-1)*2+2
      NI=0
      DO 20 I=1,NNP
      IF(X.NE.ZERO.AND.MOD(I,17).EQ.1)GO TO 20
      NI=NI+1
      NI1=(NI-1)*2+1
      NI2=(NI-1)*2+2
      IF(NI1.GT.NJ1)GO TO 20
      DELX=PCOOR(I,1)-PCOOR(J,1)
      DELY=PCOOR(I,2)-PCOOR(J,2)
      XSQ=DELX*DELX
      YSQ=DELY*DELY
      RSQ=XSQ+YSQ
      IF(RSQ.LT.EN5)THEN
          IF(NJ1.GE.NI1)THEN
                IPT=NAF(NJ1)-NJ1+NI1
                FLPSP(IPT)=ZERO
          ENDIF
```

```
          IF(NJ1.GE.NI2)THEN
                IPT=NAF(NJ1)-NJ1+NI2
                FLPSP(IPT)=ZERO
          ENDIF
          IF(NJ2.GE.NI1)THEN
                IPT=NAF(NJ2)-NJ2+NI1
                FLPSP(IPT)=ZERO
          ENDIF
          IF(NJ2.GE.NI2)THEN
                IPT=NAF(NJ2)-NJ2+NI2
                FLPSP(IPT)=ZERO
          ENDIF
         GO TO 20
      ENDIF
      Z=PCOOR(I,3)-GSE
      C=PCOOR(J,3)-GSE
      R1=DSQRT(RSQ+(Z-C)**2)
      R2=DSQRT(RSQ+(Z+C)**2)
      D1=ONE/R1
      D1CU=D1*D1*D1
      D2=ONE/R2
      D2SQ=D2*D2
      D2CU=D2*D2SQ
      DUM=ONE/(R2+Z+C)
      F1=C2*D1+D2
      F2=C2*D2CU+D1CU
      F3=TWO*C*Z*D2CU
      F4=THREE*D2SQ
      F5=C3*DUM
      F6=D2*DUM
      F7=(F1+F3+F5)*C1
      F8=(F2-F3*F4-F5*F6)*C1
      IF(NJ1.GE.NI1)THEN
          IPT=NAF(NJ1)-NJ1+NI1
          FLPSP(IPT)=F7+F8*XSQ
      ENDIF
      IF(NJ1.GE.NI2)THEN
          IPT=NAF(NJ1)-NJ1+NI2
          FLPSP(IPT)=DELX*DELY*F8
      ENDIF
      IF(NJ2.GE.NI1)THEN
          IPT=NAF(NJ2)-NJ2+NI1
          FLPSP(IPT)=DELX*DELY*F8
      ENDIF
      IF(NJ2.GE.NI2)THEN
          IPT=NAF(NJ2)-NJ2+NI2
          FLPSP(IPT)=F7+F8*YSQ
      ENDIF
20    CONTINUE
10    CONTINUE
      RETURN
      END
C-----------------------------------------------------------
      SUBROUTINE FLEXNA(NAF,NFLXS)
C
C     THIS ROUTINE CALCULATES THE NA ARRAY FOR THE
C     SOIL FLEXIBILITY MATRIX
C
      DIMENSION NAF(NFLXS)
      NAF(1)=1
      DO 10 I=2,NFLXS
10    NAF(I)=NAF(I-1)+I
      RETURN
      END
```

```
C-------------------------------------------------------------
      SUBROUTINE GLBNA(LMPSP,NAG,NGT,NFLXS,NEQ,NPILE)
C
C     THIS ROUTINE CALCULATES THE GLOBAL NA VECTOR
C
      DIMENSION LMPSP(NFLXS),NAG(NEQ)
      KOUNT=0
      DO 100 I=1,NPILE
      DO 90  J=1,17
      DO 80  K=1,5
      KOUNT=KOUNT+1
      IF(J.EQ.1)THEN
          NAG(KOUNT)=1
      ELSE
          IF(K.EQ.1)KNTMIN=KOUNT-5
          NAG(KOUNT)=KNTMIN
      ENDIF
80    CONTINUE
90    CONTINUE
100   CONTINUE
      DO 300 I=1,NFLXS
      DO 200 J=I,NFLXS
      IF(LMPSP(I).LT.LMPSP(J))THEN
             IF(NAG(LMPSP(J)).GT.LMPSP(I))NAG(LMPSP(J))=
     +LMPSP(I)
      ELSE
          IF(NAG(LMPSP(I)).GT.LMPSP(J))NAG(LMPSP(I))=
     +LMPSP(J)
      ENDIF
200   CONTINUE
300   CONTINUE
      NAG(1)=1
      DO 400 I=2,NEQ
400   NAG(I)=NAG(I-1)-NAG(I)+I+1
      NGT=NAG(NEQ)
      RETURN
      END
C-------------------------------------------------------------
      SUBROUTINE INISTF(FLPSP,PY,PCOOR,STPSP,NAF,NNP,
     +NFLXS,NFT)
C
C     THIS ROUTINES CALCULATES THE INITIAL TANGENT STIFFNESS
C     OF LINEAR SOIL SPRINGS OR NON-LINEAR SOIL SPRINGS
C     (PROPOSED BY O'NEILL ET AL.)
C
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      DIMENSION FLPSP(NFT),PY(17,6),PCOOR(NNP,3),
     +STPSP(NFLXS,NFLXS),NAF(NFLXS)
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DATA ZERO,PT5,ONE/0.0,0.5,1.0/
      WRITE(*,*)' FORMING THE SOIL FLEXIBILITY MATRIX'
      SMALL=1.D60
      DO 50 I=1,17
      IF(KSOIL.EQ.0)THEN
          RK=PY(I,2)*ELENP
          IF(GSE.GT.ZERO)THEN
             IF(I.EQ.1)VAR=1.D60
             IF(I.GT.1.AND.RK.GT.ZERO)VAR=RK
          ELSE
```

```
            IF(RK.GT.ZERO)VAR=RK
         ENDIF
      ELSEIF(KSOIL.EQ.1.OR.PY(I,1).NE.ZERO)THEN
         RK=PY(I,2)*ELENP*(PCOOR(I,3)-GSE)
         IF(GSE.GT.ZERO)THEN
            IF(I.LE.2)VAR=1.D60
            IF(I.GT.2.AND.RK.GT.ZERO)VAR=RK
         ELSE
            IF(I.EQ.1)VAR=1.D60
            IF(I.GT.1.AND.RK.GT.ZERO)VAR=RK
         ENDIF
      ELSE
         RK=ESTABL(PY(I,4))*ELENP
         IF(GSE.GT.ZERO)THEN
            IF(I.EQ.1)VAR=1.D60
            IF(I.GT.1.AND.RK.GT.ZERO)VAR=RK
         ELSE
            IF(RK.GT.ZERO)VAR=RK
         ENDIF
      ENDIF
      IF(VAR.LT.SMALL)SMALL=VAR
50    CONTINUE
      EPB=1.D3/SMALL
      J=16
      IF(X.EQ.ZERO)J=17
      NI=0
      DO 10 I=1,NNP
      IF(X.NE.ZERO.AND.MOD(I,17).EQ.1)GO TO 10
      NI=NI+1
      NI1=(NI-1)*2+1
      NI2=(NI-1)*2+2
      IPT1=NAF(NI1)
      IPT2=NAF(NI2)
      NMOD=MOD(NI,J)
      IF(NMOD.EQ.1.OR.NMOD.EQ.0)THEN
          ELEN=ELENP*PT5
      ELSE
          ELEN=ELENP
      ENDIF
      Z=PCOOR(I,3)-GSE
      IMOD=MOD(I,17)
      IF(IMOD.EQ.0)IMOD=17
      RK=PY(IMOD,2)
      PHI=PY(IMOD,1)
      IF(KSOIL.EQ.0)THEN
          IF(RK.EQ.ZERO)THEN
              FLPSP(IPT1)=FLPSP(IPT1)+EPB
              FLPSP(IPT2)=FLPSP(IPT2)+EPB
          ELSE
              FLPSP(IPT1)=FLPSP(IPT1)+ONE/(RK*ELEN)
              FLPSP(IPT2)=FLPSP(IPT2)+ONE/(RK*ELEN)
          ENDIF
      ELSEIF(KSOIL.EQ.1.OR.PHI.NE.ZERO)THEN
          IF(RK.EQ.ZERO.OR.Z.EQ.ZERO)THEN
              FLPSP(IPT1)=FLPSP(IPT1)+EPB
              FLPSP(IPT2)=FLPSP(IPT2)+EPB
          ELSE
              FLPSP(IPT1)=FLPSP(IPT1)+ONE/(RK*Z*ELEN)
              FLPSP(IPT2)=FLPSP(IPT2)+ONE/(RK*Z*ELEN)
          ENDIF
      ELSE
          C=PY(IMOD,4)
          ES=ESTABL(C)
          FLPSP(IPT1)=FLPSP(IPT1)+ONE/(ES*ELEN)
```

```
            FLPSP(IPT2)=FLPSP(IPT2)+ONE/(ES*ELEN)
        ENDIF
10      CONTINUE
        WRITE(*,*)' INVERTING THE SOIL FLEXIBILITY MATRIX'
        CALL INVERT(FLPSP,STPSP,NAF,NFLXS,NFT)
        RETURN
        END
C-------------------------------------------------------
        SUBROUTINE INVERT(FLEX,STIF,NAF,NEQ,NFT)
C
C       THIS ROUTINE CALCULATES THE INVERSE OF THE MATRIX
C       'FLEX' AND STORES IT IN THE MATRIX 'STIF'
C
C***********************************************************
C       DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C       CALCULATIONS
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
        DIMENSION FLEX(NFT),STIF(NEQ,NEQ),NAF(NEQ)
        DO 10 J=1,NEQ
        DO 10 I=1,NEQ
        IF(I.EQ.J)THEN
            STIF(I,J)=1.DO
        ELSE
            STIF(I,J)=0.DO
        ENDIF
10      CONTINUE
        CALL SUBSOL(FLEX,STIF,NAF,NEQ,NEQ,NEQ,4)
        RETURN
        END
C---------------------------------------------------------
        SUBROUTINE MULTP(STIF,NA,FORC,DISP,NEQ)
C***********************************************************
C-----MATRIX MULTIPLICATION  K * VECTOR ---
C       K IS A PROFILE STIFFNESS -----
C-----ACCOUNTS FOR PROFILE FORM OF K MATRIX -----
C-----MULTIPLIES 1) EACH COLUMN OF K
C-----           2) THEN RE-USES COLUMN FOR CURRENT ROW, UP
C                   TO DIAGONAL
C
C       WHERE   STIF IS THE PROFILE STIFFNESS MATRIX ---
C               NA IS THE POINTER FOR DIAG OF STIFFNESS
C               DISP IS THE VECTOR OF DISPLACEMENTS
C
C               FOR IS THE RESULTING FORCE VECTOR
C***********************************************************
        IMPLICIT REAL*8 (A-H,O-Z)
        DIMENSION STIF(NEQ),NA(NEQ),FORC(NEQ),DISP(NEQ)
        DO 250 JJ=1,NEQ
  250   FORC(JJ)=0.0D0
C-----FORM K*VECTOR (ONE COLUMN OF K AT A TIME) -----
        IS=1
        DO 400 L=1,NEQ
        NTERM=NA(L)-IS+1
C-----IROW IS LOWEST ROW FOR CURRENT COLUMN OF STIFFNESS
        IROW=L-NTERM+1
C-----FORM K*VECTOR FOR COLUMN L TO JUST BEFORE DIAGONAL
        ISS=IS
        VECM=DISP(L)
        IF(IROW.LE.L-1) THEN
          DO 300 JJ=IROW,L-1
          FORC(JJ)=FORC(JJ) + STIF(ISS)*VECM
  300     ISS=ISS+1
        ENDIF
```

```
C-----FORM DIAGONAL ROW VALUE (SYMMETRIC SO USE CURRENT
C     COLUMN -----
      CALL DOTP(STIF(IS),DISP(IROW),SUM,NTERM)
      FORC(L)=FORC(L)+SUM
C
C-----END NEXT COLUMN LOOP -----
  400 IS=NA(L)+1
      RETURN
      END
C-----------------------------------------------------------
       SUBROUTINE OBFOR(GLK,DISP,RINTF,EXTF,NAG,NEQ,NGT)
C
C      THIS ROUTINE CALCULATES THE OUT-OF-BALANCE FORCES IN
C      THE PILE GROUP SYSTEM
C
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      DIMENSION  GLK(NGT),DISP(NEQ),RINTF(NEQ),EXTF(NEQ),
     +NAG(NEQ)
      DATA RNONE/-1.D0/
      CALL MULTP(GLK,NAG,RINTF,DISP,NEQ)
      CALL ADDV(RINTF,EXTF,RNONE,NEQ)
      RETURN
      END
C-----------------------------------------------------------
      SUBROUTINE PRINTF(DISP,LMPSP,PY,PCOOR,OBF,SPSP,EKPT,
     +EKPB,PSPF,PF,SPRF,SF,NPEL,NEQ,NNP,NNPS,NPILE,NFLXS,
     +KFLG)
C
C     THIS ROUTINE CALCULATES AND PRINTS THE ELEMENT FORCES
C     FOR ALL  ELEMENT TYPES CONSTITUTING THE PILE GROUP
C     SYSTEM
C***********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      COMMON/OUTPUT/NUO1,NUO2
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,
     +KCYC,KSOIL,GSE,CL
      DIMENSION DISP(NEQ),LMPSP(NFLXS),PY(17,6),
     +PCOOR(NNP,3),OBF(NEQ),SPSP(NFLXS,NFLXS),
     +PSPF(NFLXS),PF(NPEL,10),SPRF(NFLXS),
     +LM(10),EKPT(10,10),EKPB(10,10),SF(NPILE,5)
      CHARACTER*70 NAME
      DATA ZERO/0.0/
      REWIND NUO2
      DO 40 K=1,NPEL
      READ(NUO2)(LM(I),I=1,10)
      DO 50 I=1,10
      PF(K,I)=ZERO
      DO 50 J=1,10
      JJ=LM(J)
      IF(MOD(K,16).EQ.1)THEN
           PF(K,I)=PF(K,I)+EKPT(I,J)*DISP(JJ)
      ELSE
           PF(K,I)=PF(K,I)+EKPB(I,J)*DISP(JJ)
      ENDIF
50    CONTINUE
40    CONTINUE
      DO 30 I=1,NNPS
```

```
      I1=(I-1)*2+1
      I2=(I-1)*2+2
      PSPF(I1)=ZERO
      PSPF(I2)=ZERO
      DO 30 J=1,NNPS
      J1=(J-1)*2+1
      J2=(J-1)*2+2
      JJ1=LMPSP(J1)
      JJ2=LMPSP(J2)
      PSPF(I1)=PSPF(I1)+SPSP(I1,J1)*DISP(JJ1)+SPSP(I1,J2)*
     +DISP(JJ2)
      PSPF(I2)=PSPF(I2)+SPSP(I2,J1)*DISP(JJ1)+SPSP(I2,J2)*
     +DISP(JJ2)
30    CONTINUE
      NI=0
      DO 32 I=1,NPEL
      IF(MOD(I,16).EQ.1)THEN
           NI=NI+1
           SF(NI,1)=PF(I,1)
           SF(NI,2)=PF(I,2)
           SF(NI,3)=PF(I,3)
           SF(NI,4)=PF(I,4)
           SF(NI,5)=PF(I,5)
      ENDIF
32    CONTINUE
      IF(X.EQ.ZERO)THEN
           NI=0
           DO 33 I=1,NNPS
           IF(MOD(I,17).EQ.1)THEN
                NI=NI+1
                I1=(I-1)*2+1
                I2=(I-1)*2+2
                SF(NI,2)=SF(NI,2)+PSPF(I1)
                SF(NI,3)=SF(NI,3)+PSPF(I2)
           ENDIF
33         CONTINUE
      ENDIF
      TFZZ=ZERO
      TFXX=ZERO
      TFYY=ZERO
      TMXX=ZERO
      TMYY=ZERO
      DO 55 NI=1,NPILE
      TFZZ=TFZZ+SF(NI,1)
      TFXX=TFXX+SF(NI,2)
      TFYY=TFYY+SF(NI,3)
      TMXX=TMXX+SF(NI,4)
55    TMYY=TMYY+SF(NI,5)
      WRITE(NUO1,556)
      CALL MPRINT(SF,NPILE,5,NUO1,NPILE,5,3)
      WRITE(NUO1,557)TFZZ,TFXX,TFYY,TMXX,TMYY
      IF(KFLG.EQ.0)THEN
         NAME='DISPLACEMENTS:'
         WRITE(NUO1,20)NAME
         CALL PRNTV2(DISP,NEQ,NUO1,0)
      ENDIF
      NAME='SUMMARY OF DISPLACEMENTS AT TOP OF PILE GROUP:'
      WRITE(NUO1,201)NAME
      CALL PRNTV2(DISP,NEQ,NUO1,1)
      IF(KFLG.EQ.0)THEN
         NAME='OUT OF BALANCE FORCES:'
         WRITE(NUO1,21)NAME
         CALL PRNTV2(OBF,NEQ,NUO1,0)
      ENDIF
```

```
      CALL OBFMAX(OBF,NEQ,FZZMAX,FXXMAX,FYYMAX,BMXMAX,
     +BMYMAX)
      WRITE(NUO1,*)
      WRITE(NUO1,25)FZZMAX,FXXMAX,FYYMAX,BMXMAX,BMYMAX
      WRITE(NUO1,*)
      IF(KFLG.EQ.0)THEN
261      FORMAT(/,1X,A,/,T23,'X',T35,'Y')
         NAME='NF+FF SOIL SPRINGS RESISTANCES (F):'
         WRITE(NUO1,261)NAME
         CALL PRNTV1(PSPF,NFLXS,NUO1)
         WRITE(NUO1,*)
      ENDIF
      WRITE(NUO1,35)SUMV(PSPF,NFLXS,1),SUMV(PSPF,NFLXS,0)
      WRITE(NUO1,75)TFXX,TFYY
      IF(KFLG.EQ.0)THEN
         CALL SPRGF(DISP,SPRF,LMPSP,PY,PCOOR,NEQ,NNP,NFLXS)
         NAME='NEAR FIELD SOIL RESISTANCE (F):'
         WRITE(NUO1,261)NAME
         CALL PRNTV1(SPRF,NFLXS,NUO1)
         NAME='PILE ELEMENT FORCES:'
         WRITE(NUO1,45)NAME
         CALL MPRINT(PF,NPEL,10,NUO1,16,5,4)
      ENDIF
      WRITE(NUO1,171)
      WRITE(NUO1,1751)
      NPIL=0
      DO 191 I=1,NPEL,16
      NPIL=NPIL+1
      AFZMAX=ZERO
      DO 181 J=I,I+15
      SIGN=1.D0
      IF(PF(J,1).LT.ZERO)SIGN=-1.D0
      F=ABS(PF(J,1))
      IF(F.GT.AFZMAX)THEN
        AFZMAX=F
        SIGMAX=SIGN
      ENDIF
181   CONTINUE
      WRITE(NUO1,1801)NPIL,SIGMAX*AFZMAX
191   CONTINUE
      WRITE(NUO1,*)
      WRITE(NUO1,172)
      WRITE(NUO1,176)
      NPIL=0
      DO 192 I=1,NPEL,16
      NPIL=NPIL+1
      AFXMAX=ZERO
      DO 182 J=I,I+15
      SIGN=1.D0
      IF(PF(J,2).LT.ZERO)SIGN=-1.D0
      F=ABS(PF(J,2))
      IF(F.GT.AFXMAX)THEN
        SIGMAX=SIGN
        IMAX=J
        AFXMAX=F
      ENDIF
182   CONTINUE
      WRITE(NUO1,180)NPIL,IMAX,ZNODE(IMAX+NPIL-1),
     +ZNODE(IMAX+NPIL),SIGMAX*AFXMAX
192   CONTINUE
      WRITE(NUO1,*)
      WRITE(NUO1,173)
      WRITE(NUO1,176)
      NPIL=0
```

```
      DO 193 I=1,NPEL,16
      NPIL=NPIL+1
      AFYMAX=ZERO
      DO 183 J=I,I+15
      SIGN=1.D0
      IF(PF(J,3).LT.ZERO)SIGN=-1.D0
      F=ABS(PF(J,3))
      IF(F.GT.AFYMAX)THEN
        IMAX=J
        AFYMAX=F
        SIGMAX=SIGN
      ENDIF
183    CONTINUE
      WRITE(NUO1,180)NPIL,IMAX,ZNODE(IMAX+NPIL-1),
     +ZNODE(IMAX+NPIL),SIGMAX*AFYMAX
193   CONTINUE
      WRITE(NUO1,*)
      WRITE(NUO1,174)
      WRITE(NUO1,177)
      NPIL=0
      DO 194 I=1,NPEL,16
      NPIL=NPIL+1
      ABXMAX=ZERO
      DO 184 J=I,I+15
      SIGN=1.D0
      IF(PF(J,4).LT.ZERO)SIGN=-1.D0
      B=ABS(PF(J,4))
      IF(B.GT.ABXMAX)THEN
        IMAX=J
        ABXMAX=B
        SIGMAX=SIGN
      ENDIF
184   CONTINUE
      WRITE(NUO1,190)NPIL,IMAX,ZNODE(IMAX+NPIL-1),
     +SIGMAX*ABXMAX
194   CONTINUE
      WRITE(NUO1,*)
      WRITE(NUO1,175)
      WRITE(NUO1,177)
      NPIL=0
      DO 195 I=1,NPEL,16
      NPIL=NPIL+1
      ABYMAX=ZERO
      DO 185 J=I,I+15
      SIGN=1.D0
      IF(PF(J,5).LT.ZERO)SIGN=-1.D0
      B=ABS(PF(J,5))
      IF(B.GT.ABYMAX)THEN
        IMAX=J
        ABYMAX=B
        SIGMAX=SIGN
      ENDIF
185   CONTINUE
      WRITE(NUO1,190)NPIL,IMAX,ZNODE(IMAX+NPIL-1),
     +SIGMAX*ABYMAX
195   CONTINUE
      WRITE(NUO1,76)
      RETURN
25    FORMAT(/,1X,' SUMMARY OF ABS MAXIMUM OUT-OF-BALANCE',
     +'FORCES: ',/,
     +T15,'FZZ = ',E10.3,2X,'(F)',/,
     +T15,'FXX = ',E10.3,2X,'(F)',/,
     +T15,'FYY = ',E10.3,2X,'(F)',/,
     +T15,'MXX = ',E10.3,2X,'(F-L)',/,
```

```
     +T15,'MYY = ',E10.3,2X,'(F-L)')
35    FORMAT(/,1X,
     +'CHECK: TOTAL LOAD CARRIED BY THE SOIL',/,
     +'       (SUM OF NF+FF SOIL SPRINGS RESISTANCES)',/,
     +'                IN X DIRECTION = ',E10.3,2X,'(F)',/,
     +'                IN Y DIRECTION = ',E10.3,2X,'(F)',/)
45    FORMAT(/,1X,A,/,T4,'PILE',T20,
     +'FZZ',T32,'FXX',T44,'FYY',T56,'MXX',T68,'MYY',/,
     +'  ELEMENT#',T20,'(F)',T32,
     +'(F)',T44,'(F)',T54,'(F-L)',T66,'(F-L)')
75    FORMAT(1X,
     +'       TOTAL LOAD APPLIED AT TOP OF PILE GROUP',/,
     +'                IN X DIRECTION = ',E10.3,2X,'(F)',/,
     +'                IN Y DIRECTION = ',E10.3,2X,'(F)')
171   FORMAT(/,
     +1X,'SUMMARY OF PILE ELEMENT FORCES:',/,
     +1X,'_______________________________',//,
     +1X,'1.  MAX AXIAL FORCE (F)',/,
     +1X,'_______________________',/)
172   FORMAT(/,
     +1X,'2.  MAX SHEAR FORCE IN X DIRECTION (F)',/,
     +1X,'______________________________________',/)
173   FORMAT(/,
     +1X,'3.  MAX SHEAR FORCE IN Y DIRECTION (F)',/,
     +1X,'______________________________________',/)
174   FORMAT(/,
     +1X,'4.  MAX BENDING MOMENT ABOUT X AXIS (F-L)',/,
     +1X,'_________________________________________',/)
175   FORMAT(/,
     +1X,'5.  MAX BENDING MOMENT ABOUT Y AXIS (F-L)',/,
     +1X,'_________________________________________',/)
1751  FORMAT(T10,'PILE',T22,'AXIAL',/,T13,'#',T22,'FORCE',/)
176   FORMAT(T10,'PILE',T22,'PILE',T36,'AT',T48,'AT',
     +/,T13,'#',T21,'ELEM#',T33,'DEPTH',T45,'DEPTH'T59,'MAX'
     +/,T29,'BELOW CAP',T41,'BELOW CAP',T60,'SF',/)
177   FORMAT(T10,'PILE',T22,'PILE',T36,'AT',
     +/,T13,'#',T21,'ELEM#',T33,'DEPTH',T47,'MAX',
     +/,T29,'BELOW CAP',T48,'BM',/)
1801  FORMAT(1X,I12,1X,F12.3)
180   FORMAT(1X,2I12,2F12.3,1X,E11.4)
190   FORMAT(1X,2I12,F12.3,1X,E11.4)
76    FORMAT(1X,
     +'**************************************************',
     +'*****************')
556   FORMAT(/,1X,'APPLIED LOADS:',/,T6,'PILE#',
     +T18,'FZZ',T28,'FXX',T38,'FYY',T48,'MXX',T58,'MYY')
557   FORMAT(/,2X,'TOTAL = ',5E10.3)
20    FORMAT(/,1X,A,/,1X,'PILE NODE#',T21,'DZZ',T33,'DXX',
     +T45,'DYY',T53,'THETAXX',T65,'THETAYY',/,T21,
     +'(L)',T33,'(L)',T45,'(L)',T55,'(RAD)',T67,
     +'(RAD)')
201   FORMAT(/,1X,A,/,T7,'PILE#',T21,'DZZ',T33,'DXX',
     +T45,'DYY',T53,'THETAXX',T65,'THETAYY',/,T21,
     +'(L)',T33,'(L)',T45,'(L)',T55,'(RAD)',T67,
     +'(RAD)')
21    FORMAT(/,1X,A,/,1X,'PILE NODE#',T21,'FZZ',T33,'FXX',
     +T45,'FYY',T57,'MXX',T69,'MYY',/,T21,'(F)',T33,
     +'(F)',T45,'(F)',T55,'(F-L)',T67,'(F-L)')
      END
C-----------------------------------------------------------
      SUBROUTINE PRNTIT(NUO)
C
C     THIS ROUTINE PRINTS THE TITLE PAGE OF OUTPUT
C
```

```
C*****************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C*****************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      COMMON/SOIL/GM,RNU
      COMMON/TIT/NPILE,MAXITN,TOLER,NDINC,TSTIF,KFLG,UNITS
      CHARACTER*70 UNITS
      WRITE(NUO,10)UNITS,KFLG,TPL,E,RINER,AREA,DIA,X,KCYC
      WRITE(NUO,11)NPILE,MAXITN,TOLER,KSOIL,GM,RNU,TSTIF
10    FORMAT(
     + T27,'::::    L   P   G   ::::',//,
     + T5,'THIS PROGRAM CALCULATES THE LATERAL',
     + ' LOAD-DEFLECTION BEHAVIOR',/,T5,'OF A PILE GROUP USING'
     + ,' FEM TECHNIQUE.',//,
     +1X,'*******************************************',
     +'***************************',//,
     + T33,'I  N  P  U  T',//,
     + T5,'UNITS ARE',T51,' : ',A,//,
     + T5,'CODE FOR PRINT OUT ',T47,'KFLG = ',I10,//,
     + T5,'TOTAL PILE LENGTH ',T50,'L = ',G10.3,T67,'(L)',/,
     + T5,'YOUNG'S MODULUS OF PILE ',T50,'E = ',G10.3,T67,
     + '(F/L^2)',/,
     + T5,'MOMENT OF INERTIA OF PILE ',T50,'I = ',G10.3,T67,
     + '(L^4)',/,
     + T5,'AREA OF CROSS SECTION OF PILE ',T50,'A = ',
     + G10.3,T67,'(L^2)',/,
     + T5,'DIA OF PILE ',T48,'DIA = ',G10.3,T67,'(L)',//,
     + T5,'PROJECTION OF PILE GROUP ABOVE ',/,
     + T12,'GROUND LEVEL ',T50,'X = ',G10.3,T67,'(L)',/,
     + T5,'# OF CYCLES OF LOAD APPLIED ',T47,'KCYC = ',I10)
11    FORMAT(/,T5,'# OF PILES IN THE GROUP ',T46,'NPILE = ',
     + I10,/,
     + T5,'MAXIMUM # OF ITERATIONS ',T45,'MAXITN = ',I10,/,
     + T5,'TOLERANCE ',T46,'TOLER = ',G10.3,T67,'(L)'//,
     + T5,'SOIL TYPE ',T46,'KSOIL = ',I10,/,
     + T5,'SHEAR MODULUS OF SOIL ',T50,'G = ',G10.3,T67,
     + '(F/L^2)',/,
     + T5,'POISSONS RATIO OF SOIL ',T48,'RNU = ',G10.3,//,
     + T5,'PILE TIP STIFFNESS',T46,'TSTIF = ',
     + G10.3,T67,'(F/L)')
      RETURN
      END
C-----------------------------------------------------
      SUBROUTINE SECSTF(DISP,FLPSP,STPSP,PY,NAF,PCOOR,
     +LM,SPRF,NNP,NNPS,NFLXS,NEQ,NFT)
C
C     THIS ROUTINE CALCULATES THE SECANT STIFFNESS OF SOIL
C     SPRINGS
C
C*******************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C*******************************************************
      DIMENSION DISP(NEQ),FLPSP(NFT),STPSP(NFLXS,NFLXS),
     +PY(17,6),NAF(NFLXS),PCOOR(NNP,3),LM(NFLXS),SPRF(NFLXS)
      DATA ZERO/0.0D0/
      WRITE(*,*)' FORMING THE SOIL FLEXIBILITY MATRIX'
      CALL SPRGF(DISP,SPRF,LM,PY,PCOOR,NEQ,NNP,NFLXS)
```

```
      BIG=ZERO
      DO 10 I=1,NNPS
      I1=(I-1)*2+1
      I2=(I-1)*2+2
      IPT1=NAF(I1)
      IPT2=NAF(I2)
      II1=LM(I1)
      II2=LM(I2)
      IF(SPRF(I1).EQ.ZERO)THEN
            GO TO 10
      ELSE
           FLPSP(IPT1)=FLPSP(IPT1)+DISP(II1)/SPRF(I1)
           IF(FLPSP(IPT1).GT.BIG)BIG=FLPSP(IPT1)
      ENDIF
      IF(SPRF(I2).EQ.ZERO)THEN
            GO TO 10
      ELSE
           FLPSP(IPT2)=FLPSP(IPT2)+DISP(II2)/SPRF(I2)
           IF(FLPSP(IPT2).GT.BIG)BIG=FLPSP(IPT2)
      ENDIF
10    CONTINUE
      BIG=BIG*1000.D0
      DO 20 I=1,NNPS
      I1=(I-1)*2+1
      I2=I1+1
      IPT1=NAF(I1)
      IPT2=NAF(I2)
      II1=LM(I1)
      II2=LM(I2)
      IF(SPRF(I1).EQ.ZERO)FLPSP(IPT1)=FLPSP(IPT1)+BIG
      IF(SPRF(I2).EQ.ZERO)FLPSP(IPT2)=FLPSP(IPT2)+BIG
20    CONTINUE
      WRITE(*,*)' INVERTING THE SOIL FLEXIBILITY MATRIX'
      CALL INVERT(FLPSP,STPSP,NAF,NFLXS,NFT)
      RETURN
      END
C-----------------------------------------------------------
      SUBROUTINE SPRGF(DISP,SPRF,LM,PY,PCOOR,NEQ,NNP,NFLXS)
C
C     THIS SUBROUTINE CALCULATES THE SOIL SPRING FORCES.
C     THE SPRING FORCES ARE HYPERBOLIC FUNCTIONS OF THE
C     SPRING DISPLACEMENTS  (AS PROPOSED BY O'NEILL ET. AL.)
C
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      DIMENSION DISP(NEQ),SPRF(NFLXS),LM(NFLXS),PY(17,6),
     +PCOOR(NNP,3)
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,KSOIL,
     +GSE,CL
      DATA ZERO,PT5/0.0,0.5/
      J=16
      IF(X.EQ.ZERO)J=17
      NI=0
      DO 10 I=1,NNP
      IF(X.NE.ZERO.AND.MOD(I,17).EQ.1)GO TO 10
      NI=NI+1
      NI1=(NI-1)*2+1
      NI2=(NI-1)*2+2
      NMOD=MOD(NI,J)
      IF(NMOD.EQ.1.OR.NMOD.EQ.0)THEN
          ELEN=ELENP*PT5
```

```
      ELSE
          ELEN=ELENP
      ENDIF
      II1=LM(NI1)
      II2=LM(NI2)
      Y1=DISP(II1)
      Y2=DISP(II2)
      IMOD=MOD(I,17)
      IF(IMOD.EQ.0)IMOD=17
      RK=PY(IMOD,2)
      IF(KSOIL.EQ.0)THEN
         SPRF(NI1)=RK*Y1*ELEN
         SPRF(NI2)=RK*Y2*ELEN
      ELSEIF(KSOIL.EQ.1)THEN
         Z=PCOOR(I,3)-GSE
         SPRF(NI1)=RK*Y1*Z*ELEN
         SPRF(NI2)=RK*Y2*Z*ELEN
      ELSE
         PHI=PY(IMOD,1)
         GAMMAD=PY(IMOD,3)
         Z=PCOOR(I,3)-GSE
         IF(PHI.EQ.ZERO)THEN
              IF(CL.EQ.ZERO)CL=CRITL(PY,PCOOR,NNP)
              C=PY(IMOD,4)
              E50=PY(IMOD,5)
              E100=PY(IMOD,6)
              P1=PCLAY(C,E50,E100,Z,Y1)
              P2=PCLAY(C,E50,E100,Z,Y2)
         ELSE
              P1=PSAND(PHI,RK,GAMMAD,Z,Y1)
              P2=PSAND(PHI,RK,GAMMAD,Z,Y2)
         ENDIF
         SPRF(NI1)=P1*ELEN
         SPRF(NI2)=P2*ELEN
      ENDIF
10    CONTINUE
      RETURN
      END
C-----------------------------------------------------
      SUBROUTINE SUBSOL(STIF,B,NA,NEQ,LEQ,NL,KK)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
C
C---- ACTIVE COLUMN EQUATION SOLVER - STIF*X = B --------
C
C     STIF = STIFFNESS MATRIX TERMS IN COMPACTED PROFILE
C            FORM
C     B    = LOADS - AFTER THE ROUTINE IT CONTAINS THE
C            DISPLACEMENTS
C
C     NL   = NUMBER OF LOAD CASES (COLUMNS OF LOADS)
C     NEQ  = NUBMER OF EQUATIONS.
C     LEQ  = NUMBER OF EQUATIONS TO REDUCE.  (SINCE THIS
C            IS A SUBSTRUCTURING EQUATION SOLVER, THE FIRST
C            LEQ EQUATIONS WILL BE REDUCED.
C     KK   = THE SOLUTION CONTROL PARAMETER
C     KK=1 LDL FACTORAZATION ONLY
C     KK=2 FORWARD REDUCTION ONLY
C     KK=3 BACKSUBSTITUTION ONLY
C     KK=4 COMPLETE SOLUTION
C
C************************************************************
C
      DIMENSION STIF(NEQ),B(NEQ,NL),NA(NEQ)
```

```
      COMMON /IOLIST/ NTM,NTR,NIN,NOT,NT1,NFL,
     +NT2,NT3,NT4,NT5
C
C-----SELECT OPTION -----
      GO TO (50,550,890,50), KK
C-----LDL DECOMPOSITION  -----
   50 IF (NEQ.EQ.1) RETURN
      DO 500 J=2,NEQ
      JH=NA(J)-NA(J-1)
      IF (JH.EQ.1) GO TO 500
      K=J-JH+1
C---- FORM U(I,J) - TOP OF COLUMN DOWN TO DIAGONAL --
      I=K
  100 NT=MIN0 (JH-J+I,NA(I)-NA(I-1))-1
      NS=NA(I)-NT
      NE=NA(I)-1
      IJ=NA(J)-J+I
      IC=IJ-NA(I)
      NSI=NS+IC
      S=0.0D0
      IF (I.EQ.J) GO TO 400
      IF(I.GT.LEQ) NT=NT+LEQ-I+1
      IF (NT.GT.0) THEN
        CALL DOTP(STIF(NS),STIF(NSI),S,NT)
        STIF(IJ)=STIF(IJ)-S
      ENDIF
      I=I+1
      GO TO 100
C---- FORM L(I,J) AND U(I,I) -----
  400 IF(I.GT.LEQ) NE=NE+LEQ-I+1
      IF(STIF(IJ).EQ.0.0D0) THEN
        WRITE (NTM,2000) I,STIF(IJ)
        WRITE (NOT,2000) I,STIF(IJ)
        STIF(IJ) = 1.0
      ENDIF
      DG=STIF(IJ)
      IF(NE.GE.NS) THEN
        DO 450 N=NS,NE
        ND=NA(K)
        K=K+1
        T=STIF(N)
        IF(STIF(ND).NE.0.0D0) THEN
          STIF(N)=STIF(N)/STIF(ND)
          S=S+STIF(N)*T
        ENDIF
  450   CONTINUE
      ENDIF
  460 STIF(IJ)=STIF(IJ)-S
C-----CHECK FOR SINGULAR MATRIX -----
      IF(STIF(IJ).EQ.0.0D0) THEN
        WRITE (NTM,2100) I,STIF(IJ)
        WRITE (NOT,2100) I,STIF(IJ)
        GO TO 500
      ENDIF
  500 CONTINUE
      IF(KK.EQ.4) GO TO 550
      RETURN
C---- FORWARD REDUCTION OF LOAD VECTOR B -----
  550 DO 860 L=1,NL
      DO 700 J=2,NEQ
      JH=NA(J)-NA(J-1)-1
      NS=NA(J)-JH
      K=J-JH
      IF(J.GT.LEQ) JH=JH+LEQ-J+1
```

```
      IF(JH.GT.0) THEN
        CALL DOTP(STIF(NS),B(K,L),S,JH)
        B(J,L)=B(J,L)-S
      ENDIF
  700 CONTINUE
  800 DO 850 I=1,LEQ
      K=NA(I)
      IF(STIF(K).NE.0.0D0) THEN
        B(I,L)=B(I,L)/STIF(K)
      ENDIF
  850 CONTINUE
  860 CONTINUE
      IF(KK.EQ.4) GO TO 890
      RETURN
C---- EVALUATION OF VECTOR X BY BACKSUBSTITUTION -----
  890 DO 960 L=1,NL
      DO 950 J=NEQ,2,-1
      K=J-NA(J)+NA(J-1)+1
      NS=NA(J-1)+1
      JH=NA(J)-NA(J-1) -1
      IF(J.GT.LEQ) JH=JH+LEQ-J+1
      IF(JH.GT.0) THEN
        S=-B(J,L)
        CALL ADDV(B(K,L),STIF(NS),S,JH)
      ENDIF
  950 CONTINUE
C
  960 CONTINUE
      RETURN
C-----------------------------------------------------
 2000 FORMAT (' EQUATION #',I4,' DIAGONAL TERM =',E15.7)
 2001 FORMAT (' EQUATION # ',I4,' REDUCTION LOST ',F6.2,'
FIGURES')
 2100 FORMAT(' EQUATION #',I4,' DIAG DEVEL =',E15.7)
      END
C-----------------------------------------------------------
      SUBROUTINE TIP(STRK,NA,TSTIF,NGT,NEQ)
C
C     THIS ROUTINE INCORPORATES THE PRESCRIBED PILE TIP
C     DISPLACEMENTS
C**********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C**********************************************************
      DIMENSION STRK(NGT),NA(NEQ)
      DO 10 I=1,NEQ
      IPOI=NA(I)
      IF(MOD(I,85).EQ.81)STRK(IPOI)=STRK(IPOI)+TSTIF
10    CONTINUE
      RETURN
      END
C-----------------------------------------------------
```

APPENDIX D
FORTRAN CODE OF PROGRAM LPG-VERSION 2 (LU)

```
C     MAIN PROGRAM - LPG VERSION 2(LU)
C                  - PROGRAMMED BY SHANMUGRAJ SUBRAMANIAN
C                  - MAY 1992
C***********************************************************
C     THIS PROGRAM CALCULATES THE LOAD-DEFLECTION BEHAVIOR
C     OF A PILE GROUP SUBJECTED TO LATERAL LOADS USING FEM
C     TECHNIQUE
C***********************************************************
C     -  CHANGE THE FOLLOWING LINES TO ALTER THE SIZE AND
C        PRECISION OF OF COMPUTER ANALYSIS OF THE PILE GROUP
C
      PARAMETER( MTOT = 550000,
     +           IPR  = 2    )
C***********************************************************
C     DEACTIVATE THE FOLLOWING LINES  FOR SINGLE PRECISION
C     CALCULATIONS

      DOUBLE PRECISION TPL,E,RINER,AREA,DIA,X,ELENP,GM,
     +RNU,TOLER,STEP,ERRDIS,ERRMAX,GSE,CL,TSTIF
C***********************************************************
      CHARACTER*70 NAME,UNITS
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      COMMON/SOIL/GM,RNU
      COMMON/OUTPUT/NUO1,NUO2
      COMMON/POINT/MFIRST,MLAST,IPRCN
      COMMON/TIT/NPILE,NPA,MAXITN,TOLER,NDINC,TSTIF,
     +KFLG,UNITS
      COMMON/BIG/A(MTOT)
      DATA ZERO/0.0/
      NUI=7
      NUO1=8
      NUO2=9
      NUO3=10
      IPRCN=IPR
      MFIRST=1
      MLAST=MTOT
      CL=ZERO
      CALL OPEN(NUI,NUO1,NUO2,NUO3)
      WRITE(*,*)' .................READING DATA'
      READ(NUI,2)NAME
      WRITE(NUO1,21)NAME
      READ(NUI,2)UNITS
      READ(NUI,*)KFLG
      READ(NUI,*)TPL,E,RINER,AREA,DIA
      READ(NUI,*)X,KCYC
      READ(NUI,*)NPILE,NPA
      READ(NUI,*)MAXITN,TOLER
      READ(NUI,*)KSOIL,GM,RNU
      READ(NUI,*)TSTIF
      WRITE(NUO1,3)
      CALL PRNTIT(NUO1)
```

```
      NNP=17*NPILE
      NNPA=17*NPA
      NNPAS=16*NPA
      IF(X.EQ.ZERO)NNPAS=17*NPA
      NEQ=5*NNPA
      NPEL=16*NPA
      NFLXAS=32*NPA
      IF(X.EQ.ZERO)NFLXAS=34*NPA
      NFLXS=32*NPILE
      IF(X.EQ.ZERO)NFLXS=34*NPILE
      MPPY=MPOINT(17,6,IPR)
      CALL MREAD(A(MPPY),17,6,NUI)
      IF(KSOIL.EQ.0)THEN
         ASSIGN 51 TO NFMT
      ELSE
         ASSIGN 5 TO NFMT
      ENDIF
      NAME='PY CURVES DATA:'
      WRITE(NUO1,NFMT)NAME
      CALL MPRINT(A(MPPY),17,6,NUO1,17,6,3)
      MPPGEO=MPOINT(NPILE,2,IPR)
      CALL MREAD(A(MPPGEO),NPILE,2,NUI)
      NAME='PILE GEOMETRY:'
      WRITE(NUO1,6)NAME
      CALL MPRINT(A(MPPGEO),NPILE,2,NUO1,NPILE,2,3)
      MPPCOO=MPOINT(NNP,3,IPR)
      CALL PILCOR(A(MPPCOO),A(MPPGEO),NPILE,NNP)
      MPNPS=MPOINT(NPILE,0,1)
      CALL VREAD(A(MPNPS),NPILE,NUI)
      NAME='PILE SYMMETRY #(S):'
      WRITE(NUO1,88)NAME
      CALL PRNTVI(A(MPNPS),NPILE,NAME,NUO1)
      WRITE(NUO1,*)
      READ(NUI,*)KTZ,KTX,KTY,KRX,KRY
      WRITE(NUO1,198)KTZ,KTX,KTY,KRX,KRY
      MPCDIS=MPOINT(NPA,5,2)
      CALL MREAD(A(MPCDIS),NPA,5,NUI)
      WRITE(NUO1,221)
      CALL MPRINT(A(MPCDIS),NPA,5,NUO1,NPA,5,3)
      READ(NUI,*)NDINC
      WRITE(NUO1,87)NDINC
      MPFPSP=MPOINT(NFLXAS,NFLXAS,IPR)
      MPOLD=MFIRST
      MPFILL=MPOINT(NFLXS,NFLXS,IPR)
      CALL FLEX(A(MPPCOO),A(MPFPSP),A(MPFILL),A(MPNPS),NNP,
     +NFLXAS,NFLXS,NPILE,NNPAS)
      MFIRST=MPOLD
      CALL MATW(A(MPFPSP),NFLXAS,NFLXAS,NUO3)
      NLDOF=NFLXAS
      MPLM=MPOINT(NFLXAS,0,1)
      CALL LMPSP(A(MPLM),NEQ,NLDOF)
      MPGLK=MPOINT(NEQ,NEQ,IPR)
      CALL ZEROM(A(MPGLK),NEQ,NEQ)
      MPEKPT=MPOINT(10,10,IPR)
      MPEKPB=MPOINT(10,10,IPR)
      MPLM1=MPOINT(10,0,1)
      NLDOF=10
      CALL ELSTFP(A(MPEKPB),NLDOF,1)
      IF(X.EQ.ZERO)THEN
          CALL COPYM(A(MPEKPB),A(MPEKPT),NLDOF,NLDOF)
      ELSE
          CALL ELSTFP(A(MPEKPT),NLDOF,0)
      ENDIF
      NNL=(NPA-1)*17+1
```

```
      DO 30 NSUM=1,NNL,17
      DO 30 NN=NSUM,(NSUM+15)
      CALL LMPEL(A(MPLM1),NN,NLDOF)
      IF(MOD(NN,17).EQ.1)THEN
          CALL ADDSTF(A(MPEKPT),A(MPGLK),A(MPLM1),NLDOF,NEQ)
      ELSE
          CALL ADDSTF(A(MPEKPB),A(MPGLK),A(MPLM1),NLDOF,NEQ)
      ENDIF
30    CONTINUE
      MPIFOR=MPOINT(5*NPA,0,1)
      MPFOR=MPOINT(5*NPA,0,IPR)
      CALL BOUND(A(MPIFOR),A(MPFOR),A(MPCDIS),A(MPGLK),
     +NEQ,NPA,KTZ,KTX,KTY,KRX,KRY)
      CALL TIP(A(MPGLK),TSTIF,NEQ)
      WRITE(NUO1,3)
      CALL MATW(A(MPGLK),NEQ,NEQ,NUO3)
      MPSPSP=MPOINT(NFLXAS,NFLXAS,IPR)
      MPINDX=MPOINT(NEQ,0,1)
      MPVV=MPOINT(NEQ,0,IPR)
      WRITE(*,*)' ::::::MAX # OF INCREMENT(S) = ',NDINC
      WRITE(*,*)' ::::::MAX # OF ITERATION(S) = ',MAXITN
      CALL INISTF(A(MPFPSP),A(MPPY),A(MPPCOO),
     +A(MPSPSP),A(MPINDX),A(MPVV),NNPA,NNP,NFLXAS)
      NLDOF=NFLXAS
      CALL ADDSTF(A(MPSPSP),A(MPGLK),A(MPLM),NLDOF,NEQ)
      MPEXTF=MPOINT(NEQ,0,IPR)
      MPINTF=MPOINT(NEQ,0,IPR)
      MPDISP=MPOINT(NEQ,0,IPR)
      MPODIS=MPOINT(NEQ,0,IPR)
      MPPSPF=MPOINT(NFLXAS,0,IPR)
      MPPF=MPOINT(NPEL,10,IPR)
      MPSPRF=MPOINT(NFLXAS,0,IPR)
      MPSF=MPOINT(NPA,5,IPR)
      WRITE(*,78)MTOT,(MFIRST-1),(MTOT-MFIRST+1)
      WRITE(NUO1,78)MTOT,(MFIRST-1),(MTOT-MFIRST+1)
      WRITE(NUO1,3)
      WRITE(NUO1,61)GSE
      IF(KFLG.EQ.0)THEN
              NAME='COORDINATES OF PILE NODES:'
              WRITE(NUO1,7)NAME
              CALL MPRINT(A(MPPCOO),NNP,3,NUO1,17,3,3)
      ENDIF
      DO 50 IN=1,NDINC
      WRITE(*,*)'INCREMENT # = ',IN
      STEP=DBLE(IN)
      CALL NULVEC(A(MPEXTF),NEQ)
      CALL NULVEC(A(MPODIS),NEQ)
      CALL EXTFOR(STEP,A(MPIFOR),A(MPFOR),A(MPEXTF),NPA,NEQ)
      ICON=0
      DO 60 IT=1,MAXITN
      WRITE(*,*)' ITERATION # = ',IT
      CALL COPYM(A(MPEXTF),A(MPDISP),NEQ,1)
      WRITE(*,*)' SOLVING THE SYSTEM EQUATIONS'
      CALL SOLVE(A(MPGLK),A(MPDISP),A(MPINDX),A(MPVV),NEQ)
      ERRDIS=ERRMAX(A(MPODIS),A(MPDISP),NEQ)
      IF(IT.NE.1.AND.ERRDIS.LE.TOLER)ICON=1
      IF(ICON.EQ.1)THEN
            REWIND NUO3
            CALL MATR(A(MPFPSP),NFLXAS,NFLXAS,NUO3)
            CALL MATR(A(MPGLK),NEQ,NEQ,NUO3)
            CALL SECSTF(A(MPDISP),A(MPFPSP),A(MPSPSP),
     +A(MPPY),A(MPINDX),A(MPVV),A(MPPCOO),A(MPLM),A(MPSPRF),NNPA,
     +NNPAS,NNP,NFLXAS,NEQ)
            CALL ADDSTF(A(MPSPSP),A(MPGLK),A(MPLM),NLDOF,NEQ)
```

```
           CALL OBFOR(A(MPGLK),A(MPDISP),A(MPINTF),
     +A(MPEXTF),NEQ)
           WRITE(NUO1,75)
           WRITE(NUO1,76)IN,IT,ERRDIS
           WRITE(NUO1,75)
           CALL PRINTF(A(MPDISP),A(MPLM),A(MPPY),A(MPPCOO),
     +A(MPINTF),A(MPSPSP),A(MPEKPT),A(MPEKPB),A(MPPSPF),A(MPPF),
     +A(MPSPRF),A(MPSF),NPEL,NEQ,NNPA,NNP,NNPAS,NPA,NFLXAS,KFLG)
           GO TO 50
      ELSE
           IF(IT.EQ.MAXITN)THEN
              WRITE(NUO1,75)
              WRITE(*,77)IN,IT,ERRDIS
              WRITE(NUO1,77)IN,IT,ERRDIS
              WRITE(NUO1,75)
              STOP
           ELSE
              REWIND NUO3
              CALL MATR(A(MPFPSP),NFLXAS,NFLXAS,NUO3)
              CALL MATR(A(MPGLK),NEQ,NEQ,NUO3)
              CALL SECSTF(A(MPDISP),A(MPFPSP),
     +A(MPSPSP),A(MPPY),A(MPINDX),A(MPVV),A(MPPCOO),A(MPLM),
     +A(MPSPRF),NNPA,NNPAS,NNP,NFLXAS,NEQ)
              CALL ADDSTF(A(MPSPSP),A(MPGLK),A(MPLM),
     +NLDOF,NEQ)
              CALL COPYM(A(MPDISP),A(MPODIS),NEQ,1)
           ENDIF
      ENDIF
60    CONTINUE
50    CONTINUE
2     FORMAT(A)
21    FORMAT(1X,A)
3     FORMAT(
     + 1X,'*******************************************',
     +'**************************',/)
5     FORMAT(/,1X,A,/,T18,'PHI',T30,'K',T35,'GAMMA`',
     +T49,'CU',T58,'E50',T67,'E100',/,T16,'(DEG)',
     +T24,'(F/L^3)',T34,'(F/L^3)',T44,
     +'(F/L^2)',T56,'(L/L)',T66,'(L/L)'/)
51    FORMAT(/,1X,A,/,T18,'PHI',T30,'K',T35,'GAMMA`',
     +T49,'CU',T58,'E50',T67,'E100',/,T16,'(DEG)',
     +T24,'(F/L^2)',T34,'(F/L^3)',T44,
     +'(F/L^2)',T56,'(L/L)',T66,'(L/L)'/)
6     FORMAT(/,1X,A,/,T6,'PILE#',T20,'X',T30,'Y')
61    FORMAT(/,
     +T22,'::::     OUTPUT     ::::',//,
     +T5,'GROUND SURFACE ELEVATION   = ',E10.3,1X,'(L)')
7     FORMAT(/,1X,A,/,T7,'PILE',T20,'X',T30,'Y',T40,'Z',/,
     +T6,'NODE#')
76    FORMAT(T5,'THE SOLUTION CONVERGED FOR:',/,
     +T5,'DISPLACEMENT/FORCE INCREMENT #   = ',I10,/,
     +T5,'                   ITERATION #   = ',I10,/,
     +T5,'MAX  DEFLECTION  ERROR           = ',E10.3,
     +1X,'(L)',/)
77    FORMAT(T5,'THE SOLUTION COULD NOT CONVERGE FOR:',/,
     +T5,'DISPLACEMENT/FORCE INCREMENT #   = ',I10,/,
     +T5,'MAX  ITERATION               #   = ',I10,/,
     +T5,'MAX  DEFLECTION  ERROR           =
     +',E10.3,1X,'(L)',/)
78    FORMAT(
     +1X,'TOTAL # OF MEMORY UNITS       = ',I10,/,
     +1X,'# OF MEMORY UNITS USED BY LPG = ',I10,/,
     +1X,'# OF MEMORY UNITS FREE        = ',I10,/)
75    FORMAT(/,
```

```
     +1X,'____________________________________'
     +,'__________________________________________',/,1X,'_________'
     +,'____________________________________________________________',
     +'____________')
87    FORMAT(/,
     +T5,'# OF CAP LOAD INCREMENT = ',I10)
88    FORMAT(/,1X,A,/,4X,'PILE #',2X,'SYMMETRY #')
198   FORMAT(1X,'BOUNDARY CONDITIONS CODE:',/,
     +1X,'  FOR TRANSLATION IN Z DIRECTION = ',I2,/,
     +1X,'                     X           = ',I2,/,
     +1X,'                     Y           = ',I2,/,
     +1X,'  FOR ROTATION ABOUT X AXIS      = ',I2,/
     +1X,'                     Y AXIS      = ',I2,/)
221   FORMAT(1X,'CAP LOADS/DISPLACEMENTS:',/,
     +T6,'PILE#',T14,'FZZ/DZZ',T24,'FXX/DXX',T34,'FYY/DYY',
     +T44,'MXX/RXX',T54,'MYY/RYY')
      END
C-----------------------------------------------------------
      SUBROUTINE ADDSTF(EKM ,GLK,LM,NLDOF,NEQ)
C
C     THIS ROUTINE ADDS THE ELEMENT STIFFNES MATRIX TO THE
C     GLOBAL STIFFNESS MATRIX
C
C**********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C**********************************************************
      DIMENSION EKM(NLDOF,NLDOF),GLK(NEQ,NEQ),LM(NLDOF)
      DO 10 I=1,NLDOF
      N=LM(I)
      DO 10 J=1,NLDOF
      M=LM(J)
      GLK(N,M)=GLK(N,M)+EKM(I,J)
10    CONTINUE
      RETURN
      END
C-----------------------------------------------------------
      SUBROUTINE BOUND(IFOR,FOR,CDIS,STRK,NEQ,NPA,
     +KTZ,KTX,KTY,KRX,KRY)
C
C     THIS ROUTINE INCORPORATES BOUNDARY CONDITIONS TO THE
C     TOP OF PILES - ->KTZ,KTX,KTY,KRX,KRY = 0 MEANS FORCE
C     BOUNDARY CONDITION AND = 1 MEANS DISPLACEMENT BOUNDARY
C**********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C**********************************************************
      COMMON/POINT/MFIRST,MLAST,IPRCN
      DIMENSION STRK(NEQ,NEQ),IFOR(5*NPA),FOR(5*NPA),
     +CDIS(NPA,5)
      EPB=0.D0
      DO 5 J=1,NEQ
      DO 4 I=1,J
      DUM=STRK(I,J)
      IF(EPB.LT.DUM)EPB=DUM
4     CONTINUE
5     CONTINUE
      EPB=1.D3*EPB
      K=0
      DO 10 I=1,NEQ
      IF(MOD(I,85).EQ.1)THEN
         K=K+1
```

```
         K1=(K-1)*5+1
         IFOR(K1)=I
         IF(KTZ.EQ.0)THEN
            FOR(K1)=CDIS(K,1)
         ELSE
            STRK(I,I)=STRK(I,I)+EPB
            FOR(K1)=STRK(I,I)*CDIS(K,1)
         ENDIF
         K1=(K-1)*5+2
         IFOR(K1)=I+1
         IF(KTX.EQ.0)THEN
            FOR(K1)=CDIS(K,2)
         ELSE
            STRK(I+1,I+1)=STRK(I+1,I+1)+EPB
            FOR(K1)=STRK(I+1,I+1)*CDIS(K,2)
         ENDIF
         K1=(K-1)*5+3
         IFOR(K1)=I+2
         IF(KTY.EQ.0)THEN
            FOR(K1)=CDIS(K,3)
         ELSE
            STRK(I+2,I+2)=STRK(I+2,I+2)+EPB
            FOR(K1)=STRK(I+2,I+2)*CDIS(K,3)
         ENDIF
         K1=(K-1)*5+4
         IFOR(K1)=I+3
         IF(KRX.EQ.0)THEN
            FOR(K1)=CDIS(K,4)
         ELSE
            STRK(I+3,I+3)=STRK(I+3,I+3)+EPB
            FOR(K1)=STRK(I+3,I+3)*CDIS(K,4)
         ENDIF
         K1=(K-1)*5+5
         IFOR(K1)=I+4
         IF(KRY.EQ.0)THEN
            FOR(K1)=CDIS(K,5)
         ELSE
            STRK(I+4,I+4)=STRK(I+4,I+4)+EPB
            FOR(K1)=STRK(I+4,I+4)*CDIS(K,5)
         ENDIF
      ENDIF
10    CONTINUE
      RETURN
      END
C-----------------------------------------------------------
      SUBROUTINE EXTFOR(STEP,IFOR,FOR,EXTF,NPA,NEQ)
C
C     THIS ROUTINE CALCULATES THE EXTERNAL FORCES APPLIED
C     TO THE PILE GROUP SYSTEM
C
C**********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C**********************************************************
      DIMENSION IFOR(5*NPA),FOR(5*NPA),EXTF(NEQ)
      IMAX=5*NPA
      DO 10 I=1,IMAX
      II=IFOR(I)
      EXTF(II)=FOR(I)*STEP
10    CONTINUE
      RETURN
      END
C-----------------------------------------------------------
```

```
      SUBROUTINE FLEX(PCOOR,FLPSP,FLPSP1,NPS,NNP,NFLXAS,
     +NFLXS,NPILE,NNPAS)
C
C     THIS ROUTINE CALCULTES PILE-SOIL-PILE FLEXIBILITY BY
C     MINDLIN FLEXIBILITY EQNS FOR  POINT FORCES APPLIED AT
C     A POINT INSIDE AN ELASTIC CONTINUUM IN X AND Y
C     DIRECTIONS
C***********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      COMMON/SOIL/GM,RNU
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DIMENSION PCOOR(NNP,3),FLPSP(NFLXAS,NFLXAS),
     +FLPSP1(NFLXS,NFLXS),NPS(NPILE)
      DATA PI,ZERO,ONE,TWO,THREE,FOUR,RN16,EN5
     +/3.1415927,0.0,1.0,2.0,3.0,4.0,16.0,0.00001/
      C1=ONE/(RN16*PI*GM*(ONE-RNU))
      C2=THREE-FOUR*RNU
      C3=FOUR*(ONE-RNU)*(ONE-TWO*RNU)
      NJ=0
      DO 10 J=1,NNP
      IF(X.NE.ZERO.AND.MOD(J,17).EQ.1)GO TO 10
      NJ=NJ+1
      NJ1=(NJ-1)*2+1
      NJ2=(NJ-1)*2+2
      NI=0
      DO 20 I=1,NNP
      IF(X.NE.ZERO.AND.MOD(I,17).EQ.1)GO TO 20
      NI=NI+1
      NI1=(NI-1)*2+1
      NI2=(NI-1)*2+2
      IF(NI1.GT.NJ1)GO TO 20
      DELX=PCOOR(I,1)-PCOOR(J,1)
      DELY=PCOOR(I,2)-PCOOR(J,2)
      XSQ=DELX*DELX
      YSQ=DELY*DELY
      RSQ=XSQ+YSQ
      IF(RSQ.LT.EN5)THEN
         FLPSP1(NI1,NJ1)=ZERO
         FLPSP1(NI2,NJ1)=ZERO
         FLPSP1(NI1,NJ2)=ZERO
         FLPSP1(NI2,NJ2)=ZERO
         GO TO 20
      ENDIF
      Z=PCOOR(I,3)-GSE
      C=PCOOR(J,3)-GSE
      R1=DSQRT(RSQ+(Z-C)**2)
      R2=DSQRT(RSQ+(Z+C)**2)
      D1=ONE/R1
      D1CU=D1*D1*D1
      D2=ONE/R2
      D2SQ=D2*D2
      D2CU=D2*D2SQ
      DUM=ONE/(R2+Z+C)
      F1=C2*D1+D2
      F2=C2*D2CU+D1CU
      F3=TWO*C*Z*D2CU
      F4=THREE*D2SQ
      F5=C3*DUM
      F6=D2*DUM
```

```
      F7=(F1+F3+F5)*C1
      F8=(F2-F3*F4-F5*F6)*C1
      FLPSP1(NI1,NJ1)=F7+F8*XSQ
      FLPSP1(NI2,NJ1)=DELX*DELY*F8
      FLPSP1(NI1,NJ2)=FLPSP1(NI2,NJ1)
      FLPSP1(NI2,NJ2)=F7+F8*YSQ
20    CONTINUE
10    CONTINUE
      DO 25 J=1,NFLXAS-1
      DO 25 I=J+1,NFLXAS
      FLPSP1(I,J)=FLPSP1(J,I)
25    CONTINUE
C
C---------INVOKE SYMMETRY------------------------------
C
      JJ=16
      IF(X.EQ.ZERO)JJ=17
      DO 30 I=1,NNPAS
      I1=(I-1)*2+1
      I2=(I-1)*2+2
      DO 40 J=1,NPILE
      IF(NPS(J).EQ.J)GO TO 40
      DO 50 K=1,JJ
      NXI=(NPS(J)-1)*JJ+K
      NXC=(J-1)*JJ+K
      NXI1=(NXI-1)*2+1
      NXI2=(NXI-1)*2+2
      NXC1=(NXC-1)*2+1
      NXC2=(NXC-1)*2+2
      FLPSP1(I1,NXI1)=FLPSP1(I1,NXI1)+FLPSP1(I1,NXC1)
      FLPSP1(I2,NXI1)=FLPSP1(I2,NXI1)+FLPSP1(I2,NXC1)
      FLPSP1(I1,NXI2)=FLPSP1(I1,NXI2)+FLPSP1(I1,NXC2)
      FLPSP1(I2,NXI2)=FLPSP1(I2,NXI2)+FLPSP1(I2,NXC2)
50    CONTINUE
40    CONTINUE
30    CONTINUE
C
C---------CONDENSE FLEXIBILITY MATRIX 'FLPSP1' INTO 'FLPSP'
C--------- AFTER INVOKING SYMMETRY-------------
      DO 60 I=1,NFLXAS
      DO 60 J=1,NFLXAS
60    FLPSP(I,J)=FLPSP1(I,J)
      RETURN
      END
C-----------------------------------------------------
      SUBROUTINE INISTF(FLPSP,PY,PCOOR,STPSP,INDX,VV,
     +NNPA,NNP,NFLXAS)
C
C     THIS ROUTINE CALCULATES THE INITIAL TANGENT STIFFNESS
C     OF LINEAR SOIL SPRINGS OR NON-LINEAR SOIL SPRINGS
C     (PROPOSED BY O'NEILL ET. AL.)
C*****************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C******************************************************
      DIMENSION FLPSP(NFLXAS,NFLXAS),PY(17,6),PCOOR(NNP,3),
     +STPSP(NFLXAS,NFLXAS),INDX(NFLXAS),VV(NFLXAS)
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DATA ZERO,PT5,ONE/0.0,0.5,1.0/
      WRITE(*,*)' FORMING THE SOIL FLEXIBILITY MATRIX'
      SMALL=1.D60
      DO 50 I=1,17
```

```
      IF(KSOIL.EQ.0)THEN
          RK=PY(I,2)*ELENP
          IF(GSE.GT.ZERO)THEN
             IF(I.EQ.1)VAR=1.D60
             IF(I.GT.1.AND.RK.GT.ZERO)VAR=RK
          ELSE
             IF(RK.GT.ZERO)VAR=RK
          ENDIF
      ELSEIF(KSOIL.EQ.1.OR.PY(I,1).NE.ZERO)THEN
         RK=PY(I,2)*ELENP*(PCOOR(I,3)-GSE)
         IF(GSE.GT.ZERO)THEN
            IF(I.LE.2)VAR=1.D60
            IF(I.GT.2.AND.RK.GT.ZERO)VAR=RK
         ELSE
            IF(I.EQ.1)VAR=1.D60
            IF(I.GT.1.AND.RK.GT.ZERO)VAR=RK
         ENDIF
      ELSE
         RK=ESTABL(PY(I,4))*ELENP
         IF(GSE.GT.ZERO)THEN
            IF(I.EQ.1)VAR=1.D60
            IF(I.GT.1.AND.RK.GT.ZERO)VAR=RK
         ELSE
            IF(RK.GT.ZERO)VAR=RK
         ENDIF
      ENDIF
      IF(VAR.LT.SMALL)SMALL=VAR
50    CONTINUE
      EPB=1.D3/SMALL
      J=16
      IF(X.EQ.ZERO)J=17
      NI=0
      DO 10 I=1,NNPA
      IF(X.NE.ZERO.AND.MOD(I,17).EQ.1)GO TO 10
      NI=NI+1
      NI1=(NI-1)*2+1
      NI2=(NI-1)*2+2
      NMOD=MOD(NI,J)
      IF(NMOD.EQ.1.OR.NMOD.EQ.0)THEN
          ELEN=ELENP*PT5
      ELSE
          ELEN=ELENP
      ENDIF
      Z=PCOOR(I,3)-GSE
      IMOD=MOD(I,17)
      IF(IMOD.EQ.0)IMOD=17
      RK=PY(IMOD,2)
      PHI=PY(IMOD,1)
      IF(KSOIL.EQ.0)THEN
          IF(RK.EQ.ZERO)THEN
             FLPSP(NI1,NI1)=FLPSP(NI1,NI1)+EPB
             FLPSP(NI2,NI2)=FLPSP(NI2,NI2)+EPB
          ELSE
             FLPSP(NI1,NI1)=FLPSP(NI1,NI1)+ONE/(RK*ELEN)
             FLPSP(NI2,NI2)=FLPSP(NI2,NI2)+ONE/(RK*ELEN)
          ENDIF
      ELSEIF(KSOIL.EQ.1.OR.PHI.NE.ZERO)THEN
          IF(RK.EQ.ZERO.OR.Z.EQ.ZERO)THEN
             FLPSP(NI1,NI1)=FLPSP(NI1,NI1)+EPB
             FLPSP(NI2,NI2)=FLPSP(NI2,NI2)+EPB
          ELSE
             FLPSP(NI1,NI1)=FLPSP(NI1,NI1)+ONE/(RK*Z*ELEN)
             FLPSP(NI2,NI2)=FLPSP(NI2,NI2)+ONE/(RK*Z*ELEN)
          ENDIF
```

```
      ELSE
          C=PY(IMOD,4)
          ES=ESTABL(C)
          FLPSP(NI1,NI1)=FLPSP(NI1,NI1)+ONE/(ES*ELEN)
          FLPSP(NI2,NI2)=FLPSP(NI2,NI2)+ONE/(ES*ELEN)
      ENDIF
10    CONTINUE
      WRITE(*,*)' INVERTING THE SOIL FLEXIBILITY MATRIX'
      CALL INVERT(FLPSP,STPSP,INDX,VV,NFLXAS)
      RETURN
      END
C-----------------------------------------------------------
      SUBROUTINE INVERT(A,B,INDX,VV,N)
C
C     THIS ROUTINE INVERTS THE MATRIX 'A' INTO 'B' BY USING
C     THE ROUTINES 'LUDCMP' AND 'LUBKSB'
C**********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      DIMENSION A(N,N),B(N,N),INDX(N),VV(N)
      DATA ZERO,ONE/0.0,1.0/
      DO 12 I=1,N
      DO 11 J=1,N
      B(I,J)=ZERO
11    CONTINUE
      B(I,I)=ONE
12    CONTINUE
      CALL LUDCMP(A,INDX,VV,D,N)
      DO 13 J=1,N
      CALL LUBKSB(A,INDX,B(1,J),N)
13    CONTINUE
      RETURN
      END
C-----------------------------------------------------------
      SUBROUTINE LUBKSB(A,INDX,B,N)
C
C     THIS ROUTINE BACK SUBSTITUTES THE MATRIX 'A' (WHICH
C     HAS BEEN BEEN MODIFIED BY THE ROUTINE 'LUDCMP') INTO
C     THE VECTOR 'B' AND MODIFIES IT SO AS TO FIND THE ROOTS
C     OF SIMULTANEOUS EQNS OR FIND THE INVERSE OF A SQUARE
C     MATRIX
C***********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      DIMENSION A(N,N),INDX(N),B(N)
      DATA ZERO/0.0/
      II=0
      DO 12 I=1,N
      LL=INDX(I)
      SUM=B(LL)
      B(LL)=B(I)
      IF(II.NE.0)THEN
          DO 11 J=II,I-1
          SUM=SUM-A(I,J)*B(J)
11        CONTINUE
      ELSEIF(SUM.NE.ZERO)THEN
          II=I
      ENDIF
      B(I)=SUM
12    CONTINUE
```

```
      DO 14 I=N,1,-1
      SUM=B(I)
      IF(I.LT.N)THEN
          DO 13 J=I+1,N
          SUM=SUM-A(I,J)*B(J)
13        CONTINUE
      ENDIF
      B(I)=SUM/A(I,I)
14    CONTINUE
      RETURN
      END
C------------------------------------------------------------
      SUBROUTINE LUDCMP(A,INDX,VV,D,N)
C
C     THIS ROUTINE DECOMPOSES THE MATRIX 'A' INTO LOWER AND
C     UPPER TRIANGULAR MATRICES
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      DIMENSION A(N,N),INDX(N),VV(N)
      DATA TINY,ZERO,ONE/1.0D-20,0.0,1.0/
      D=ONE
      DO 12 I=1,N
      AAMAX=ZERO
      DO 11 J=1,N
      IF(DABS(A(I,J)).GT.AAMAX)AAMAX=DABS(A(I,J))
11    CONTINUE
      IF(AAMAX.EQ.ZERO)THEN
           WRITE(*,*)'SINGULAR MATRIX'
           STOP
      ENDIF
      VV(I)=ONE/AAMAX
12    CONTINUE
      DO 19 J=1,N
      IF(J.GT.1)THEN
           DO 14 I=1,J-1
           SUM=A(I,J)
           IF(I.GT.1)THEN
              DO 13 K=1,I-1
              SUM=SUM-A(I,K)*A(K,J)
13            CONTINUE
              A(I,J)=SUM
           ENDIF
14         CONTINUE
      ENDIF
      AAMAX=ZERO
      DO 16 I=J,N
      SUM=A(I,J)
      IF(J.GT.1)THEN
          DO 15 K=1,J-1
          SUM=SUM-A(I,K)*A(K,J)
15        CONTINUE
          A(I,J)=SUM
      ENDIF
      DUM=VV(I)*DABS(SUM)
      IF(DUM.GE.AAMAX)THEN
          IMAX=I
          AAMAX=DUM
      ENDIF
16    CONTINUE
      IF(J.NE.IMAX)THEN
          DO 17 K=1,N
```

```
           DUM=A(IMAX,K)
           A(IMAX,K)=A(J,K)
           A(J,K)=DUM
17         CONTINUE
           D=-D
           VV(IMAX)=VV(J)
       ENDIF
       INDX(J)=IMAX
       IF(J.NE.N)THEN
           IF(A(J,J).EQ.ZERO)A(J,J)=TINY
           DUM=ONE/A(J,J)
           DO 18 I=J+1,N
           A(I,J)=A(I,J)*DUM
18         CONTINUE
       ENDIF
19     CONTINUE
       IF(A(N,N).EQ.ZERO)A(N,N)=TINY
       RETURN
       END
C-----------------------------------------------------------
        SUBROUTINE OBFOR(GLK,DISP,RINTF,EXTF,NEQ)
C
C       THIS ROUTINE CALCULATES THE OUT-OF-BALANCE FORCES IN
C       THE PILE GROUP SYSTEM
C***********************************************************
C      DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C      CALCULATIONS
       IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
       DIMENSION  GLK(NEQ,NEQ),DISP(NEQ),RINTF(NEQ),EXTF(NEQ)
       DATA ZERO,RNONE/0.D0,-1.D0/
       DO 40 I=1,NEQ
       SUM=ZERO
       DO 20 K=1,NEQ
       SUM=SUM+GLK(I,K)*DISP(K)
20     CONTINUE
       RINTF(I)=SUM
40     CONTINUE
       CALL ADDV(RINTF,EXTF,RNONE,NEQ)
       RETURN
       END
C-----------------------------------------------------------
       SUBROUTINE PRINTF(DISP,LMPSP,PY,PCOOR,OBF,
      +SPSP,EKPT,EKPB,PSPF,PF,SPRF,SF,NPEL,NEQ,
      +NNPA,NNP,NNPAS,NPA,NFLXAS,KFLG)
C
C      THIS ROUTINE CALCULATES AND PRINTS THE ELEMENT FORCES
C      FOR ALL  ELEMENT TYPES CONSTITUTING THE PILE GROUP
C      SYSTEM
C***********************************************************
C      DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C      CALCULATIONS
       IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
       COMMON/OUTPUT/NUO1,NUO2
       COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
      +KSOIL,GSE,CL
       DIMENSION DISP(NEQ),LMPSP(NFLXAS),PY(17,6),
      +PCOOR(NNP,3),OBF(NEQ),SPSP(NFLXAS,NFLXAS),
      +PSPF(NFLXAS),PF(NPEL,10),SPRF(NFLXAS),
      +LM(10),EKPT(10,10),EKPB(10,10),SF(NPA,5)
       CHARACTER*70 NAME
       DATA ZERO/0.0/
       REWIND NUO2
```

```
      DO 40 K=1,NPEL
      READ(NUO2)(LM(I),I=1,10)
      DO 50 I=1,10
      PF(K,I)=ZERO
      DO 50 J=1,10
      JJ=LM(J)
      IF(MOD(K,16).EQ.1)THEN
           PF(K,I)=PF(K,I)+EKPT(I,J)*DISP(JJ)
      ELSE
           PF(K,I)=PF(K,I)+EKPB(I,J)*DISP(JJ)
      ENDIF
50    CONTINUE
40    CONTINUE
      DO 30 I=1,NNPAS
      I1=(I-1)*2+1
      I2=(I-1)*2+2
      PSPF(I1)=ZERO
      PSPF(I2)=ZERO
      DO 30 J=1,NNPAS
      J1=(J-1)*2+1
      J2=(J-1)*2+2
      JJ1=LMPSP(J1)
      JJ2=LMPSP(J2)
      PSPF(I1)=PSPF(I1)+SPSP(I1,J1)*DISP(JJ1)+
     ++SPSP(I1,J2)*DISP(JJ2)
      PSPF(I2)=PSPF(I2)+SPSP(I2,J1)*DISP(JJ1)+
     ++SPSP(I2,J2)*DISP(JJ2)
30    CONTINUE
      NI=0
      DO 32 I=1,NPEL
      IF(MOD(I,16).EQ.1)THEN
           NI=NI+1
           SF(NI,1)=PF(I,1)
           SF(NI,2)=PF(I,2)
           SF(NI,3)=PF(I,3)
           SF(NI,4)=PF(I,4)
           SF(NI,5)=PF(I,5)
      ENDIF
32    CONTINUE
      IF(X.EQ.ZERO)THEN
           NI=0
           DO 33 I=1,NNPAS
           IF(MOD(I,17).EQ.1)THEN
                NI=NI+1
                I1=(I-1)*2+1
                I2=(I-1)*2+2
                SF(NI,2)=SF(NI,2)+PSPF(I1)
                SF(NI,3)=SF(NI,3)+PSPF(I2)
           ENDIF
33         CONTINUE
      ENDIF
      TFZZ=ZERO
      TFXX=ZERO
      TFYY=ZERO
      TMXX=ZERO
      TMYY=ZERO
      DO 55 NI=1,NPA
      TFZZ=TFZZ+SF(NI,1)
      TFXX=TFXX+SF(NI,2)
      TFYY=TFYY+SF(NI,3)
      TMXX=TMXX+SF(NI,4)
55    TMYY=TMYY+SF(NI,5)
      WRITE(NUO1,556)
      CALL MPRINT(SF,NPA,5,NUO1,NPA,5,3)
```

```
      WRITE(NUO1,557)TFZZ,TFXX,TFYY,TMXX,TMYY
      IF(KFLG.EQ.0)THEN
         NAME='DISPLACEMENTS:'
         WRITE(NUO1,20)NAME
         CALL PRNTV2(DISP,NEQ,NUO1,0)
      ENDIF
      NAME='SUMMARY OF DISPLACEMENTS AT TOP OF PILE GROUP:'
      WRITE(NUO1,201)NAME
      CALL PRNTV2(DISP,NEQ,NUO1,1)
      IF(KFLG.EQ.0)THEN
         NAME='OUT OF BALANCE FORCES:'
         WRITE(NUO1,21)NAME
         CALL PRNTV2(OBF,NEQ,NUO1,0)
      ENDIF
      CALL OBFMAX(OBF,NEQ,FZZMAX,FXXMAX,FYYMAX,
     +BMXMAX,BMYMAX)
      WRITE(NUO1,*)
      WRITE(NUO1,25)FZZMAX,FXXMAX,FYYMAX,BMXMAX,BMYMAX
      WRITE(NUO1,*)
      IF(KFLG.EQ.0)THEN
261      FORMAT(/,1X,A,/,T23,'X',T35,'Y')
         NAME='NF+FF SOIL SPRINGS RESISTANCES (F):'
         WRITE(NUO1,261)NAME
         CALL PRNTV1(PSPF,NFLXAS,NUO1)
         WRITE(NUO1,*)
      ENDIF
      WRITE(NUO1,35)SUMV(PSPF,NFLXAS,1),SUMV(PSPF,NFLXAS,0)
      WRITE(NUO1,75)TFXX,TFYY
      IF(KFLG.EQ.0)THEN
         CALL SPRGF(DISP,SPRF,LMPSP,PY,PCOOR,NEQ,
     +NNPA,NNP,NFLXAS)
         NAME='NEAR FIELD SOIL RESISTANCE (F):'
         WRITE(NUO1,261)NAME
         CALL PRNTV1(SPRF,NFLXAS,NUO1)
         NAME='PILE ELEMENT FORCES:'
         WRITE(NUO1,45)NAME
         CALL MPRINT(PF,NPEL,10,NUO1,16,5,4)
      ENDIF
      WRITE(NUO1,171)
      WRITE(NUO1,1751)
      NPIL=0
      DO 191 I=1,NPEL,16
      NPIL=NPIL+1
      AFZMAX=ZERO
      DO 181 J=I,I+15
      SIGN=1.D0
      IF(PF(J,1).LT.ZERO)SIGN=-1.D0
      F=ABS(PF(J,1))
      IF(F.GT.AFZMAX)THEN
        AFZMAX=F
        SIGMAX=SIGN
      ENDIF
181   CONTINUE
      WRITE(NUO1,1801)NPIL,SIGMAX*AFZMAX
191   CONTINUE
      WRITE(NUO1,*)
      WRITE(NUO1,172)
      WRITE(NUO1,176)
      NPIL=0
      DO 192 I=1,NPEL,16
      NPIL=NPIL+1
      AFXMAX=ZERO
      DO 182 J=I,I+15
      SIGN=1.D0
```

```
      IF(PF(J,2).LT.ZERO)SIGN=-1.D0
      F=ABS(PF(J,2))
      IF(F.GT.AFXMAX)THEN
        SIGMAX=SIGN
        IMAX=J
        AFXMAX=F
      ENDIF
182   CONTINUE
      WRITE(NUO1,180)NPIL,IMAX,ZNODE(IMAX+NPIL-1),
     +ZNODE(IMAX+NPIL),SIGMAX*AFXMAX
192   CONTINUE
      WRITE(NUO1,*)
      WRITE(NUO1,173)
      WRITE(NUO1,176)
      NPIL=0
      DO 193 I=1,NPEL,16
      NPIL=NPIL+1
      AFYMAX=ZERO
      DO 183 J=I,I+15
      SIGN=1.D0
      IF(PF(J,3).LT.ZERO)SIGN=-1.D0
      F=ABS(PF(J,3))
      IF(F.GT.AFYMAX)THEN
        IMAX=J
        AFYMAX=F
        SIGMAX=SIGN
      ENDIF
183    CONTINUE
      WRITE(NUO1,180)NPIL,IMAX,ZNODE(IMAX+NPIL-1),
     +ZNODE(IMAX+NPIL),SIGMAX*AFYMAX
193   CONTINUE
      WRITE(NUO1,*)
      WRITE(NUO1,174)
      WRITE(NUO1,177)
      NPIL=0
      DO 194 I=1,NPEL,16
      NPIL=NPIL+1
      ABXMAX=ZERO
      DO 184 J=I,I+15
      SIGN=1.D0
      IF(PF(J,4).LT.ZERO)SIGN=-1.D0
      B=ABS(PF(J,4))
      IF(B.GT.ABXMAX)THEN
        IMAX=J
        ABXMAX=B
        SIGMAX=SIGN
      ENDIF
184   CONTINUE
      WRITE(NUO1,190)NPIL,IMAX,ZNODE(IMAX+NPIL-1),
     +SIGMAX*ABXMAX
194   CONTINUE
      WRITE(NUO1,*)
      WRITE(NUO1,175)
      WRITE(NUO1,177)
      NPIL=0
      DO 195 I=1,NPEL,16
      NPIL=NPIL+1
      ABYMAX=ZERO
      DO 185 J=I,I+15
      SIGN=1.D0
      IF(PF(J,5).LT.ZERO)SIGN=-1.D0
      B=ABS(PF(J,5))
      IF(B.GT.ABYMAX)THEN
        IMAX=J
```

```
        ABYMAX=B
        SIGMAX=SIGN
       ENDIF
185    CONTINUE
       WRITE(NUO1,190)NPIL,IMAX,ZNODE(IMAX+NPIL-1),
      +SIGMAX*ABYMAX
195    CONTINUE
       WRITE(NUO1,76)
       RETURN
25     FORMAT(/,1X,' SUMMARY OF ABS MAXIMUM OUT-OF-BALANCE'
      +,'FORCES: ',/,
      +T15,'FZZ = ',E10.3,2X,'(F)',/,
      +T15,'FXX = ',E10.3,2X,'(F)',/,
      +T15,'FYY = ',E10.3,2X,'(F)',/,
      +T15,'MXX = ',E10.3,2X,'(F-L)',/,
      +T15,'MYY = ',E10.3,2X,'(F-L)')
35     FORMAT(/,1X,
      +'CHECK: TOTAL LOAD CARRIED BY THE SOIL',/,
      +'       (SUM OF NF+FF SOIL SPRINGS RESISTANCES)',/,
      +'                   IN X DIRECTION = ',E10.3,2X,'(F)',/,
      +'                   IN Y DIRECTION = ',E10.3,2X,'(F)',/)
45     FORMAT(/,1X,A,/,T4,'PILE',T20,
      +'FZZ',T32,'FXX',T44,'FYY',T56,'MXX',T68,'MYY',/,
      +'  ELEMENT#',T20,'(F)',T32,
      +'(F)',T44,'(F)',T54,'(F-L)',T66,'(F-L)')
75     FORMAT(1X,
      +'       TOTAL LOAD APPLIED AT TOP OF PILE GROUP',/,
      +'                   IN X DIRECTION = ',E10.3,2X,'(F)',/,
      +'                   IN Y DIRECTION = ',E10.3,2X,'(F)')
171    FORMAT(/,
      +1X,'SUMMARY OF PILE ELEMENT FORCES:',/,
      +1X,'______________________________',//,
      +1X,'1.  MAX AXIAL FORCE (F)',/,
      +1X,'_______________________',/)
172    FORMAT(/,
      +1X,'2.  MAX SHEAR FORCE IN X DIRECTION (F)',/,
      +1X,'______________________________________',/)
173    FORMAT(/,
      +1X,'3.  MAX SHEAR FORCE IN Y DIRECTION (F)',/,
      +1X,'______________________________________',/)
174    FORMAT(/,
      +1X,'4.  MAX BENDING MOMENT ABOUT X AXIS (F-L)',/,
      +1X,'_________________________________________',/)
175    FORMAT(/,
      +1X,'5.  MAX BENDING MOMENT ABOUT Y AXIS (F-L)',/,
      +1X,'_________________________________________',/)
1751   FORMAT(T10,'PILE',T22,'AXIAL',/,T13,'#',T22,'FORCE',/)
176    FORMAT(T10,'PILE',T22,'PILE',T36,'AT',T48,'AT',
      +/,T13,'#',T21,'ELEM#',T33,'DEPTH',T45,'DEPTH'T59,'MAX'
      +/,T29,'BELOW CAP',T41,'BELOW CAP',T60,'SF',/)
177    FORMAT(T10,'PILE',T22,'PILE',T36,'AT',
      +/,T13,'#',T21,'ELEM#',T33,'DEPTH',T47,'MAX',
      +/,T29,'BELOW CAP',T48,'BM',/)
1801   FORMAT(1X,I12,1X,IF12.3)
180    FORMAT(1X,2I12,2F12.3,1X,E11.4)
190    FORMAT(1X,2I12,F12.3,1X,E11.4)
76     FORMAT(1X,
      +'*********************************************',
      +'**********************')
556    FORMAT(/,1X,'APPLIED LOADS:',/,T6,'PILE#',
      +T18,'FZZ',T28,'FXX',T38,'FYY',T48,'MXX',T58,'MYY')
557    FORMAT(/,2X,'TOTAL = ',5E10.3)
20     FORMAT(/,1X,A,/,1X,'PILE NODE#',T21,'DZZ',T33,'DXX',
      +T45,'DYY',T53,'THETAXX',T65,'THETAYY',/,T21,
```

```
     +'(L)',T33,'(L)',T45,'(L)',T55,'(RAD)',T67,
     +'(RAD)')
201   FORMAT(/,1X,A,/,T7,'PILE#',T21,'DZZ',T33,
     +'DXX',T45,'DYY',T53,'THETAXX',T65,'THETAYY',/,T21,
     +'(L)',T33,'(L)',T45,'(L)',T55,'(RAD)',T67,'(RAD)')
21    FORMAT(/,1X,A,/,1X,'PILE NODE#',T21,'FZZ',T33,
     +'FXX',T45,'FYY',T57,'MXX',T69,'MYY',/,T21,'(F)',
     +T33,'(F)',T45,'(F)',T55,'(F-L)',T67,'(F-L)')
      END
C-----------------------------------------------------------
      SUBROUTINE PRNTIT(NUO)
C
C     THIS ROUTINE PRINTS THE TITLE PAGE OF OUTPUT
C***********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      COMMON/SOIL/GM,RNU
      COMMON/TIT/NPILE,NPA,MAXITN,TOLER,NDINC,
     +TSTIF,KFLG,UNITS
      CHARACTER*70 UNITS
      WRITE(NUO,10)UNITS,KFLG,TPL,E,RINER,AREA,DIA,X,KCYC
      WRITE(NUO,11)NPILE,NPA,MAXITN,TOLER,KSOIL,GM,RNU,TSTIF
10    FORMAT(
     + T27,'::::    L   P   G   ::::',//,
     + T5,'THIS PROGRAM CALCULATES THE LATERAL'
     + ,' LOAD-DEFLECTION BEHAVIOR',/,T5,'OF A PILE GROUP'
     + ' USING FEM TECHNIQUE.',//,
     + 1X,'********************************'
     +,'****************************************',//,
     + T33,'I  N  P  U  T',//,
     + T5,'UNITS ARE',T51,' : ',A,//,
     + T5,'CODE FOR PRINT OUT ',T47,'KFLG = ',I10,//,
     + T5,'TOTAL PILE LENGTH ',T50,'L = ',G10.3,T67,'(L)',/,
     + T5,'YOUNG`S MODULUS OF PILE ',T50,'E = ',G10.3,
     + T67,'(F/L^2)',/,
     + T5,'MOMENT OF INERTIA OF PILE ',T50,'I = ',G10.3,
     + T67,'(L^4)',/,
     + T5,'AREA OF CROSS SECTION OF PILE ',T50,'A = ',G10.3,
     + T67,'(L^2)',/,
     + T5,'DIA OF PILE ',T48,'DIA = ',G10.3,T67,'(L)',//,
     + T5,'PROJECTION OF PILE GROUP ABOVE ',/,
     + T12,'GROUND LEVEL ',T50,'X = ',G10.3,T67,'(L)',/,
     + T5,'# OF CYCLES OF LOAD APPLIED ',T47,'KCYC = ',I10)
11    FORMAT(/,T5,'# OF PILES IN THE GROUP ',T46,
     + 'NPILE = ',I10,/,
     + T5,'# OF ASYMMETRIC PILES IN THE GROUP',T48,
     + 'NPA = ',I10,//,
     + T5,'MAXIMUM # OF ITERATIONS ',T45,'MAXITN = ',I10,/,
     + T5,'TOLERANCE ',T46,'TOLER = ',G10.3,T67,'(L)'//,
     + T5,'SOIL TYPE ',T46,'KSOIL = ',I10,/,
     + T5,'SHEAR MODULUS OF SOIL ',T50,'G = ',G10.3,
     + T67,'(F/L^2)',/,
     + T5,'POISSONS RATIO OF SOIL ',T48,'RNU = ',G10.3,//,
     + T5,'PILE TIP STIFFNESS',T46,'TSTIF = ',G10.3,
     + T67,'(F/L)')
      RETURN
      END
C-----------------------------------------------------------
      SUBROUTINE PRNTVI(IA,N,NAME,NUO)
C
```

```
C     THIS ROUTINE PRINTS AN INTEGER VECTOR OF SIZE N
C****************************************************************
      DIMENSION IA(N)
      DO 10 I=1,N
      IF(MOD(I,16).EQ.1.AND.I.NE.1)WRITE(NUO,*)
      WRITE(NUO,15)I,IA(I)
10    CONTINUE
      RETURN
15    FORMAT(I9,2X,I10)
      END
C----------------------------------------------------------------
      SUBROUTINE SECSTF(DISP,FLPSP,STPSP,PY,INDX,VV,
     +PCOOR,LM,SPRF,NNPA,NNPAS,NNP,NFLXAS,NEQ)
C
C     THIS ROUTINE CALCULATES THE SECANT STIFFNESS OF SOIL
C     SPRINGS
C****************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C****************************************************************
      DIMENSION DISP(NEQ),FLPSP(NFLXAS,NFLXAS),
     +STPSP(NFLXAS,NFLXAS),PY(17,6),INDX(NFLXAS),
     +VV(NFLXAS),PCOOR(NNP,3),LM(NFLXAS),SPRF(NFLXAS)
      DATA ZERO/0.0/
      WRITE(*,*)' FORMING THE SOIL FLEXIBILITY MATRIX'
      CALL SPRGF(DISP,SPRF,LM,PY,PCOOR,NEQ,NNPA,NNP,NFLXAS)
      BIG=ZERO
      DO 10 I=1,NNPAS
      I1=(I-1)*2+1
      I2=(I-1)*2+2
      II1=LM(I1)
      II2=LM(I2)
      IF(SPRF(I1).EQ.ZERO)THEN
          GO TO 10
      ELSE
          FLPSP(I1,I1)=FLPSP(I1,I1)+DISP(II1)/SPRF(I1)
          IF(FLPSP(I1,I1).GT.BIG)BIG=FLPSP(I1,I1)
      ENDIF
      IF(SPRF(I2).EQ.ZERO)THEN
          GO TO 10
      ELSE
          FLPSP(I2,I2)=FLPSP(I2,I2)+DISP(II2)/SPRF(I2)
          IF(FLPSP(I2,I2).GT.BIG)BIG=FLPSP(I2,I2)
      ENDIF
10    CONTINUE
      BIG=BIG*1000.D0
      DO 20 I=1,NNPAS
      I1=(I-1)*2+1
      I2=(I-1)*2+2
      II1=LM(I1)
      II2=LM(I2)
      IF(SPRF(I1).EQ.ZERO)FLPSP(I1,I1)=FLPSP(I1,I1)+BIG
      IF(SPRF(I2).EQ.ZERO)FLPSP(I2,I2)=FLPSP(I2,I2)+BIG
20    CONTINUE
      WRITE(*,*)' INVERTING THE SOIL FLEXIBILITY MATRIX'
      CALL INVERT(FLPSP,STPSP,INDX,VV,NFLXAS)
      RETURN
      END
C---------------------------------------------------------------
      SUBROUTINE SOLVE(A,B,INDX,VV,N)
C
C     THIS ROUTINE SOLVES SIMULTANEOUS EQNS A * X = B . THE
C     VECTOR 'X' IS OVERWRITTEN ON THE VECTOR 'B'.
```

```
C*********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C*********************************************************
      DIMENSION A(N,N),B(N),INDX(N),VV(N)
      CALL LUDCMP(A,INDX,VV,D,N)
      CALL LUBKSB(A,INDX,B,N)
      RETURN
      END
C---------------------------------------------------------
      SUBROUTINE SPRGF(DISP,SPRF,LM,PY,PCOOR,NEQ,
     +NNPA,NNP,NFLXAS)
C
C     THIS SUBROUTINE CALCULATES THE SOIL SPRING FORCES.
C     THE SPRING FORCES ARE HYPERBOLIC FUNCTIONS OF THE
C     SPRING DISPLACEMENTS  (AS PROPOSED BY O'NEILL ET AL.)
C*********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C*********************************************************
      DIMENSION DISP(NEQ),SPRF(NFLXAS),LM(NFLXAS),PY(17,6),
     +PCOOR(NNP,3)
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DATA ZERO,PT5/0.0,0.5/
      J=16
      IF(X.EQ.ZERO)J=17
      NI=0
      DO 10 I=1,NNPA
      IF(X.NE.ZERO.AND.MOD(I,17).EQ.1)GO TO 10
      NI=NI+1
      NI1=(NI-1)*2+1
      NI2=(NI-1)*2+2
      NMOD=MOD(NI,J)
      IF(NMOD.EQ.1.OR.NMOD.EQ.0)THEN
          ELEN=ELENP*PT5
      ELSE
          ELEN=ELENP
      ENDIF
      II1=LM(NI1)
      II2=LM(NI2)
      Y1=DISP(II1)
      Y2=DISP(II2)
      IMOD=MOD(I,17)
      IF(IMOD.EQ.0)IMOD=17
      RK=PY(IMOD,2)
      IF(KSOIL.EQ.0)THEN
         SPRF(NI1)=RK*Y1*ELEN
         SPRF(NI2)=RK*Y2*ELEN
      ELSEIF(KSOIL.EQ.1)THEN
         Z=PCOOR(I,3)-GSE
         SPRF(NI1)=RK*Y1*Z*ELEN
         SPRF(NI2)=RK*Y2*Z*ELEN
      ELSE
         PHI=PY(IMOD,1)

         GAMMAD=PY(IMOD,3)

         Z=PCOOR(I,3)-GSE
         IF(PHI.EQ.ZERO)THEN
              IF(CL.EQ.ZERO)CL=CRITL(PY,PCOOR,NNP)
              C=PY(IMOD,4)
```

```
                E50=PY(IMOD,5)
                E100=PY(IMOD,6)
                P1=PCLAY(C,E50,E100,Z,Y1)
                P2=PCLAY(C,E50,E100,Z,Y2)
           ELSE
                P1=PSAND(PHI,RK,GAMMAD,Z,Y1)
                P2=PSAND(PHI,RK,GAMMAD,Z,Y2)

           ENDIF
           SPRF(NI1)=P1*ELEN
           SPRF(NI2)=P2*ELEN
        ENDIF
10      CONTINUE
        RETURN
        END
C------------------------------------------------------------
        SUBROUTINE TIP(STRK,TSTIF,NEQ)
C
C       THIS ROUTINE INCORPORATES THE PRESCRIBED PILE TIP
C       DISPLACEMENTS
C************************************************************
C       DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C       CALCULATIONS
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
        DIMENSION STRK(NEQ,NEQ)
        DO 10 I=1,NEQ
        IF(MOD(I,85).EQ.81)STRK(I,I)=STRK(I,I)+TSTIF
10      CONTINUE
        RETURN
        END
C------------------------------------------------------------
        SUBROUTINE VREAD(IA,N,NOT)
C       THIS ROUTINE READS INTEGER VECTOR A OF SIZE N
C************************************************************
        DIMENSION IA(N)
        READ(NOT,*)(IA(I),I=1,N)
        RETURN
        END
C------------------------------------------------------------
        SUBROUTINE ZEROM(A,N,M)
C
C       THIS ROUTINE ZEROS A MATRIX OF SIZE N X M
C************************************************************
C       DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C       CALCULATIONS
        IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
        DIMENSION A(N,M)
        DATA ZERO/0.0/
        DO 10 J=1,M
        DO 10 I=1,N
           A(I,J)=ZERO
10      CONTINUE
        RETURN
        END
C------------------------------------------------------------
```

APPENDIX E
FORTRAN SUBROUTINES COMMON TO LPG-VERSIONS 1 AND 2

```
      SUBROUTINE ADDV(A,B,S,N)
C
C     THIS ROUTINE ADDS TWO VECTORS 'A' AND 'B'.  VECTOR 'B'
C     IS FACTORED BY A SCALAR 'S' BEFORE ADDING
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      DIMENSION A(N),B(N)
      DO 300 I=1,N
  300 A(I)=A(I)+B(I)*S
      RETURN
      END
C------------------------------------------------------------
      SUBROUTINE COPYM(A,B,NR,NC)
C     THIS ROUTINE COPIES THE CONTENTS OF MATRIX 'A' INTO
C     MATRIX 'B'
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      DIMENSION A(NR,NC),B(NR,NC)
      DO 10 J=1,NC
      DO 10 I=1,NR
10    B(I,J)=A(I,J)
      RETURN
      END
C------------------------------------------------------------
      FUNCTION CRITL(PY,PCOOR,NNP)
C
C     THIS ROUTINE CALCULATES THE CRITICAL LENGTH OF PILE AS
C     SUGGESTED BY O'NEILL
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DIMENSION PY(17,6),PCOOR(NNP,3)
      DATA ZERO,TOLER,PT286,THREE,FIVE
     +/0.0,0.001,0.286,3.0,5.0/
      CLMAX=TPL-GSE
      CRITL=FIVE*DIA
      DO 10 KOUNT=1,100
      NI=0
      ESSUM=ZERO
      DO 20 I=1,17
      IF(I.EQ.1.AND.X.NE.ZERO)GO TO 20
```

```
      Z=PCOOR(I,3)-GSE
      NI=NI+1
      IF(Z.LT.CRITL)THEN
          ZOLD=Z
          IF(PY(I,1).EQ.ZERO)THEN
              ESOLD=ESTABL(PY(I,4))
          ELSE
              ESOLD=PY(I,2)*Z
          ENDIF
          ESSUM=ESSUM+ESOLD
      ELSE
          ZNEW=Z
          IF(PY(I,1).EQ.ZERO)THEN
              ESNEW=ESTABL(PY(I,4))
          ELSE
              ESNEW=PY(I,2)*Z
          ENDIF
          ESCL=ESOLD+(ESNEW-ESOLD)/(ZNEW-ZOLD)*(CRITL-ZOLD)
          ESSUM=ESSUM+ESCL
          GO TO 30
      ENDIF
20    CONTINUE
30    ESAVG=ESSUM/DBLE(NI)
      CRITLN=THREE*(E*RINER/ESAVG/DSQRT(DIA))**PT286
      ERR=DABS((CRITLN-CRITL)/CRITLN)
      CRITL=CRITLN
      IF(CRITL.GT.CLMAX)CRITL=CLMAX
      IF(ERR.LE.TOLER)RETURN
10    CONTINUE
      RETURN
      END
C-------------------------------------------------------------
      SUBROUTINE ELSTFP(EKP,NLDOF,K)
C
C     THIS ROUTINE CALCULATES THE ELEMENT STIFFNESS OF A
C     PILE SEGMENT
C
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DIMENSION EKP(NLDOF,NLDOF)
      DATA ZERO,TWO,FOUR,SIX,RN12/0.0,2.0,4.0,6.0,12.0/
      ELEN=ELENP
      IF(K.EQ.0)ELEN=X
      AEL=AREA*E/ELEN
      EI=E*RINER
      EIL=EI/ELEN
      EIL2=EIL/ELEN
      EIL3=EIL2/ELEN
      EKP(1,1)=AEL
      EKP(1,2)=ZERO
      EKP(2,2)=RN12*EIL3
      EKP(1,3)=ZERO
      EKP(2,3)=ZERO
      EKP(3,3)=RN12*EIL3
      EKP(1,4)=ZERO
      EKP(2,4)=ZERO
      EKP(3,4)=-SIX*EIL2
      EKP(4,4)=FOUR*EIL
      EKP(1,5)=ZERO
```

```
      EKP(2,5)=SIX*EIL2
      EKP(3,5)=ZERO
      EKP(4,5)=ZERO
      EKP(5,5)=FOUR*EIL
      EKP(1,6)=-AEL
      DO 10 I=2,5
10    EKP(I,6)=ZERO
      EKP(6,6)=AEL
      EKP(1,7)=ZERO
      EKP(2,7)=-RN12*EIL3
      EKP(3,7)=ZERO
      EKP(4,7)=ZERO
      EKP(5,7)=-SIX*EIL2
      EKP(6,7)=ZERO
      EKP(7,7)=RN12*EIL3
      EKP(1,8)=ZERO
      EKP(2,8)=ZERO
      EKP(3,8)=-RN12*EIL3
      EKP(4,8)=SIX*EIL2
      DO 20 I=5,7
20    EKP(I,8)=ZERO
      EKP(8,8)=RN12*EIL3
      EKP(1,9)=ZERO
      EKP(2,9)=ZERO
      EKP(3,9)=-SIX*EIL2
      EKP(4,9)=TWO*EIL
      DO 30 I=5,7
30    EKP(I,9)=ZERO
      EKP(8,9)=SIX*EIL2
      EKP(9,9)=FOUR*EIL
      EKP(1,10)=ZERO
      EKP(2,10)=SIX*EIL2
      EKP(3,10)=ZERO
      EKP(4,10)=ZERO
      EKP(5,10)=TWO*EIL
      EKP(6,10)=ZERO
      EKP(7,10)=-SIX*EIL2
      EKP(8,10)=ZERO
      EKP(9,10)=ZERO
      EKP(10,10)=FOUR*EIL
      DO 40 J=1,9
      DO 40 I=J+1,10
40    EKP(I,J)=EKP(J,I)
      RETURN
      END
C-------------------------------------------------------------
      FUNCTION ERRMAX(ODIS,DIS,N)
C
C     THIS ROUTINE CALCULATES THE MAXIMUM  ERROR
C     BETWEEN THE VECTORS 'ODIS' AND 'DIS'
C*************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C*************************************************************
      DIMENSION ODIS(N),DIS(N)
      DATA ZERO/0.0/
      ERRMAX=ZERO
      DO 20 I=1,N
      ERR=DABS(ODIS(I)-DIS(I))
20    IF(ERR.GT.ERRMAX)ERRMAX=ERR
      RETURN
      END
C-------------------------------------------------------------
```

```
      FUNCTION ESTABL(C)
C
C     THIS ROUTINE RETURNS THE VALUE OF 'ES - YOUNGS MODULUS
C     OF SOIL' FOR INPUT  OF 'CU - UNDRAINED SHEAR STRENGTH
C     OF CLAY' VALUE AS PER THE CORRELATION SUGGESTED BY
C     BANERJEE AND DAVIS
C***********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      ESTABL=100.D0*C
      RETURN
      END
C-----------------------------------------------------------
      FUNCTION FTABL(E100)
C
C     THIS ROUTINE RETURNS THE VALUE OF 'F - DEGRADATION
C     FACTOR' FOR INPUT OF 'E100 - UU TRIAXIAL FAILURE
C     STRAIN OF THE SOIL'
C***********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DIMENSION EDAT(2),FDAT(5)
      DATA EDAT,FDAT/0.02,0.06,0.5,0.33,0.75,0.67,1.0/
      IF(E100.LT.EDAT(1))THEN
          IF(KCYC.EQ.0)THEN
             FTABL=FDAT(1)
          ELSE
             FTABL=FDAT(2)
          ENDIF
      ELSEIF(E100.LE.EDAT(2))THEN
          IF(KCYC.EQ.0)THEN
             FTABL=FDAT(3)
          ELSE
             FTABL=FDAT(4)
          ENDIF
      ELSE
          FTABL=FDAT(5)
      ENDIF
      RETURN
      END
C-----------------------------------------------------------
      SUBROUTINE LMPEL(LM,K,NLDOF)
C
C     THIS ROUTINE CALCULATES THE LOCATION MATRIX FOR THE
C     PILE ELEMENTS OF THE PILE GROUP
C***********************************************************
      COMMON/OUTPUT/NUO1,NUO2
      DIMENSION LM(NLDOF)
      KK=(K-1)*5
      DO 10 I=1,NLDOF
10    LM(I)=KK+I
      WRITE(NUO2)(LM(I),I=1,NLDOF)
      RETURN
      END
C-----------------------------------------------------------
      SUBROUTINE LMPSP(LM,NEQ,NLDOF)
C
C     THIS ROUTINE FORMS THE LOCATION MATRIX FOR
```

```
C     PILE-SOIL-PILE FORCES
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DIMENSION LM(NLDOF)
      DATA ZERO/0.0/
      J=0
      DO 10 I=2,NEQ,5
      IF(X.NE.ZERO.AND.MOD(I,85).EQ.2)GO TO 10
      J=J+1
      LM(J)=I
      J=J+1
      LM(J)=I+1
10    CONTINUE
      RETURN
      END
C------------------------------------------------------------
      SUBROUTINE MATR(A,N,M,NUO)
C
C     THIS ROUTINE READS A MATRIX FROM A UNFORMATTED
C     'SCRATCH' FILE. MAXIMUM LENGTH OF RECORD WRITTEN =
C     MAXLRC
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      COMMON/POINT/MFIRST,MLAST,IPRCN
      DIMENSION A(*)
      DATA MAXLRC/32000/
      NM=N*M
      NTERM=MAXLRC/IPRCN/4
      LENGTH=NM*IPRCN*4
      NLOOP=(LENGTH-1)/MAXLRC+1
      NS=1
      NF=NTERM
      DO 100 I=1,NLOOP
      IF(NF.GT.NM)NF=NM
      READ(NUO)(A(J),J=NS,NF)
      NS=NF+1
100   NF=NS+NTERM-1
      RETURN
      END
C------------------------------------------------------------
      SUBROUTINE MATW(A,N,M,NUO)
C
C     THIS ROUTINE WRITES A MATRIX ON A UNFORMATTED
C     'SCRATCH' FILE. MAXIMUM LENGTH OF RECORD WRITTEN =
C     MAXLRC
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      COMMON/POINT/MFIRST,MLAST,IPRCN
      DIMENSION A(*)
      DATA MAXLRC/32000/
      NM=N*M
      NTERM=MAXLRC/IPRCN/4
      LENGTH=NM*IPRCN*4
```

```
      NLOOP=(LENGTH-1)/MAXLRC+1
      NS=1
      NF=NTERM
      DO 100 I=1,NLOOP
      IF(NF.GT.NM)NF=NM
      WRITE(NUO)(A(J),J=NS,NF)
      NS=NF+1
100   NF=NS+NTERM-1
      RETURN
      END
C-------------------------------------------------------------
      FUNCTION MPOINT(NDIM1,NDIM2,IP)
C
C     THIS ROUTINE CALCULATES THE POSITION OF MEMORY STORAGE
C     POINTER
C*************************************************************
      COMMON/POINT/MFIRST,MLAST,IPRCN
      MPOINT=MFIRST
      IF(IPRCN.EQ.2.AND.MOD(MPOINT,2).EQ.0)MPOINT=MPOINT+1
      IF(NDIM2.EQ.0)THEN
         MFIRST=MPOINT+NDIM1*IP
      ELSE
         MFIRST=MPOINT+NDIM1*NDIM2*IP
      ENDIF
      IF(MFIRST.GT.MLAST)THEN
         WRITE(*,*)'STORAGE EXCEEDED BY ',(MFIRST-MLAST),'
     +UNITS'
         STOP
      ENDIF
      RETURN
      END
C------------------------------------------------------------
      SUBROUTINE MPRINT(A,NR,NC,NOS,NLP,NCP,KFRMT)
C
C     THIS ROUTINE PRINTS A MATRIX OF SIZE NR X NC
C
C*************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C*************************************************************
      DIMENSION A(NR,NC)
      IF(KFRMT.EQ.4)THEN
         ASSIGN 31 TO NFMT1
         ASSIGN 26 TO NFMT2
      ELSE
         ASSIGN 30 TO NFMT1
         ASSIGN 25 TO NFMT2
      ENDIF
      DO 10 J=1,NC,NCP
      JH=J+NCP-1
      IF(JH.GT.NC)JH=NC
      WRITE(NOS,NFMT2)(N,N=J,JH)
      DO 20 I=1,NR
      IF(MOD(I,NLP).EQ.1.AND.I.NE.1)WRITE(NOS,*)
      WRITE(NOS,NFMT1)I,(A(I,K),K=J,JH)
20    CONTINUE
10    CONTINUE
      WRITE(NOS,*)
      RETURN
25    FORMAT(10X,7I10)
26    FORMAT(10X,7I12)
30    FORMAT(1X,I9,7E10.3)
```

```
31    FORMAT(1X,I9,7(1X,E11.4))
      END
C------------------------------------------------------------
      SUBROUTINE MREAD(A,N,M,NOT)
C
C     THIS ROUTINE READS A MATRIX OF SIZE N X M
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      DIMENSION A(N,M)
      DO 10 I=1,N
10    READ(NOT,*)(A(I,J),J=1,M)
      RETURN
      END
C------------------------------------------------------------
      SUBROUTINE NULVEC(A,N)
C
C     THIS ROUTINE ZEROS A VECTOR OF SIZE N
C
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      DIMENSION A(N)
      DATA ZERO/0.0/
      DO 10 I=1,N
      A(I)=ZERO
10    CONTINUE
      RETURN
      END
C------------------------------------------------------------
      SUBROUTINE OBFMAX(OBF,N,FZZMAX,FXXMAX,FYYMAX,
     +BMXMAX,BMYMAX)
C
C     THIS ROUTINE CALCULATES MAXIMUM OUT-OF-BALANCE FORCES
C     IN VECTOR 'OBF' OF SIZE  N
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      DIMENSION OBF(N)
      DATA ZERO/0.0/
      FZZMAX=ZERO
      FXXMAX=ZERO
      FYYMAX=ZERO
      BMXMAX=ZERO
      BMYMAX=ZERO
      DO 10 I=1,N
      ABSOBF=DABS(OBF(I))
      IF(MOD(I,5).EQ.1)THEN
          IF(ABSOBF.GT.FZZMAX)FZZMAX=ABSOBF
      ELSEIF(MOD(I,5).EQ.2)THEN
          IF(ABSOBF.GT.FXXMAX)FXXMAX=ABSOBF
      ELSEIF(MOD(I,5).EQ.3)THEN
          IF(ABSOBF.GT.FYYMAX)FYYMAX=ABSOBF
      ELSEIF(MOD(I,5).EQ.4)THEN
          IF(ABSOBF.GT.BMXMAX)BMXMAX=ABSOBF
      ELSE
          IF(ABSOBF.GT.BMYMAX)BMYMAX=ABSOBF
```

```
      ENDIF
10    CONTINUE
      RETURN
      END
C------------------------------------------------------------
      SUBROUTINE OPEN(NUI,NUO1,NUO2,NUO3)
C
C     THIS ROUTINE OPENS INPUT AND OUTPUT FILES
C************************************************************
      CHARACTER*15 FINP,FOUT
      WRITE(*,*)'INPUT DATA FILE NAME'
      READ(*,10)FINP
      WRITE(*,*)'OUTPUT DATA FILE NAME'
      READ(*,10)FOUT
      OPEN(UNIT=NUI,FILE=FINP,FORM='FORMATTED',
     +STATUS='UNKNOWN')
      OPEN(UNIT=NUO1,FILE=FOUT,FORM='FORMATTED',
     +STATUS='UNKNOWN')
      OPEN(UNIT=NUO2,FORM='UNFORMATTED',STATUS='SCRATCH')
      OPEN(UNIT=NUO3,FORM='UNFORMATTED',STATUS='SCRATCH')
10    FORMAT(A15)
      RETURN
      END
C------------------------------------------------------------
      FUNCTION PCLAY(C,E50,E100,Z,Y)
C
C     THIS ROUTINE CALCULATES THE SOIL RESISTANCE 'P'  USING
C     THE P-Y CURVE  SUGGESTED BY O'NEILL FOR CLAY
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DATA ZERO,PT125,PT25,PT387,PT5,PT8,ONE,SIX,NINE,
     +TEN,RN14,TWENTY
     +/0.0,0.125,0.25,0.387,0.5,0.8,1.0,6.0,9.0,
     +10.0,14.0,20.0/
      YD=Y
      IF(Y.LT.ZERO)YD=-YD
      AD=PT8
      ES=ESTABL(C)
      YC=AD*E50*DSQRT(DIA)*(E*RINER/ES)**PT125
      F=FTABL(E100)
      PU=PUCLAY(Z,C,F)
      YYC=YD/YC
      ZCRIT=CL*PT25
      IF(KCYC.EQ.0)THEN
           IF(YYC.LE.SIX)THEN
              PCLAY=PU*PT5*YYC**PT387
           ELSE
              IF(Z.GE.ZCRIT)THEN
                 PCLAY=PU
              ELSE
                 FAC=F+(ONE-F)*Z/ZCRIT
                 PUD=FAC*PU
                 IF(YYC.LT.TWENTY)THEN
                    PCLAY=PU+(PUD-PU)/RN14*(YYC-SIX)
                 ELSE
                    PCLAY=PUD
                 ENDIF
              ENDIF
           ENDIF
```

```
      ELSE
           IF(YYC.LE.ONE)THEN
              PCLAY=PU*PT5*YYC*PT387
           ELSE
              IF(Z.GE.ZCRIT)THEN
                 PCLAY=PU*PT5
              ELSE
                 FAC=PT5*F*Z/ZCRIT
                 PUD=FAC*PU
                 IF(YYC.LT.TEN)THEN
                   PCLAY=PU*PT5+(PUD-PU*PT5)/NINE*(YYC-ONE)
                 ELSE
                   PCLAY=PUD
                 ENDIF
              ENDIF
           ENDIF
      ENDIF
      IF(Y.LT.ZERO)PCLAY=-PCLAY
      RETURN
      END
C------------------------------------------------------------
      SUBROUTINE PILCOR(PCOOR,PGEOM,NPILE,NNP)
C
C     THIS ROUTINE CALCULATES PILE COORDINATES
C
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C************************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DIMENSION PCOOR(NNP,3),PGEOM(NPILE,2)
      DATA ZERO,RN15,RN16/0.0,15.,16./
      X1=X
      GSE=X
      IF(X1.EQ.ZERO)THEN
          X1=TPL/RN16
          GSE=ZERO
      ENDIF
      ELENP=(TPL-X1)/RN15
      DO 10 J=1,NPILE
      N=(J-1)*17+1
      PCOOR(N,1)=PGEOM(J,1)
      PCOOR(N,2)=PGEOM(J,2)
      PCOOR(N,3)=ZERO
      PCOOR(N+1,1)=PGEOM(J,1)
      PCOOR(N+1,2)=PGEOM(J,2)
      PCOOR(N+1,3)=X1
      DO 20 I=N+2,N+16
      PCOOR(I,1)=PGEOM(J,1)
      PCOOR(I,2)=PGEOM(J,2)
      PCOOR(I,3)=PCOOR(I-1,3)+ELENP
20    CONTINUE
10    CONTINUE
      RETURN
      END
C------------------------------------------------------------
      SUBROUTINE PRNTV1(PSPF,NEQ,NUO)
C
C     THIS ROUTINE PRINTS VECTOR 'PSPF' AFTER SPLITTING INTO
C     ODD AND EVEN NUMBERED COMPONENTS
C************************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
```

```
C     CALCULATIONS
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DIMENSION PSPF(NEQ)
      NUM=17
      IF(GSE.GT.0.D0)NUM=16
      WRITE(NUO,20)
20    FORMAT(1X,T23,'1',T35,'2')
      NODE=0
      DO 25 I=1,NEQ
      IF(MOD(I,2).EQ.1)THEN
          NODE=NODE+1
          PSPFX=PSPF(I)
          IF(MOD(NODE,NUM).EQ.1.AND.NODE.NE.1)WRITE(NUO,*)
      ELSE
          PSPFY=PSPF(I)
          WRITE(NUO,30)NODE,PSPFX,PSPFY
      ENDIF
25    CONTINUE
      RETURN
30    FORMAT(2X,I9,2X,E10.3,2X,E10.3)
      END
C-----------------------------------------------------------
      SUBROUTINE PRNTV2(DISP,NEQ,NUO,KFLG)
C
C     THIS ROUTINE PRINTS VECTOR 'DISP' AFTER SPLITTING INTO
C     FIVE COMPONENTS (DZZ,DXX,DYY,THETAXX,THETAYY)
C
C***********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      DIMENSION DISP(NEQ)
      WRITE(NUO,20)
20    FORMAT(1X,T23,'1',T35,'2',T47,'3',T59,'4',T71,'5')
      NODE=0
      DO 25 I=1,NEQ
      IF(KFLG.EQ.1.AND.MOD(I,85).GT.5)GO TO 25
      IF(KFLG.EQ.1.AND.MOD(I,85).EQ.0)GO TO 25
      IF(MOD(I,5).EQ.1)THEN
          NODE=NODE+1
          DZZ=DISP(I)
          IF(MOD(NODE,17).EQ.1.AND.NODE.NE.1.AND.
     +KFLG.EQ.0)WRITE(NUO,*)
      ELSEIF(MOD(I,5).EQ.2)THEN
          DXX=DISP(I)
      ELSEIF(MOD(I,5).EQ.3)THEN
          DYY=DISP(I)
      ELSEIF(MOD(I,5).EQ.4)THEN
          RXX=DISP(I)
      ELSE
          RYY=DISP(I)
          WRITE(NUO,30)NODE,DZZ,DXX,DYY,RXX,RYY
      ENDIF
25    CONTINUE
      WRITE(NUO,*)
      RETURN
30    FORMAT(2X,I9,5(1X,E11.4))
      END
```

```
C-----------------------------------------------------------
      FUNCTION PSAND(PHI,RK,GAMMAD,Z,Y)
C
C     THIS ROUTINE CALCULATES THE SOIL RESISTANCE 'P'  USING
C     THE P-Y CURVE  SUGGESTED BY O'NEILL FOR SAND
C***********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DATA ZERO,PT8,PT9,ONE,THREE,TWENTY
     +/0.0,0.8,0.9,1.0,3.0,20.0/
      ETA=ONE
      PU=PUSAND(GAMMAD,PHI,DIA,Z)
      IF(KCYC.EQ.0)THEN
            A=THREE-PT8*Z/DIA
            IF(A.LT.PT9)A=PT9
      ELSE
            A=PT9
      ENDIF
      IF(PU.EQ.ZERO)THEN
            FAC=ZERO
      ELSE
            ARG=RK*Z/(A*ETA*PU)*Y
            IF(DABS(ARG).GT.TWENTY)THEN
               IF(ARG.GT.ZERO)THEN
                  ARG=TWENTY
               ELSE
                  ARG=-TWENTY
               ENDIF
            ENDIF
            FAC=ETA*A*DTANH(ARG)
      ENDIF
      PSAND=FAC*PU
      RETURN
      END
C-----------------------------------------------------------
      FUNCTION PUCLAY(Z,C,F)
C
C     THIS ROUTINE CALCULATES THE ULTIMATE LATERAL
C     RESISTANCE OF CLAY AT ANY DEPTH Z (AS PROPOSED BY
C     O'NEILL)
C***********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C***********************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DATA PT25,THREE,SIX,NINE/0.25,3.0,6.0,9.0/
      ZCRIT=CL*PT25
      RNP=THREE+SIX*Z/ZCRIT
      IF(RNP.GT.NINE)RNP=NINE
      PUCLAY=F*RNP*C*DIA
      RETURN
      END
C-----------------------------------------------------------
      FUNCTION PUSAND(GAMMAD,PHI1,DIA,Z)
C
C     THIS ROUTINE CALCULATES THE ULTIMATE LATERAL
C     RESISTANCE OF SAND AT ANY DEPTH Z (AS PROPOSED BY
C     REESE,KOCH AND KOOP)
```

```
C**********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C**********************************************************
      DATA PI,PT25,PT5,ONE,TWO,RN180/3.1415927,0.25,0.5,1.0
     +,2.0,180.0/
      PHI=PHI1/RN180*PI
      BETA=PI*PT25+PHI*PT5
      SPHI=DSIN(PHI)
      TPHI=DTAN(PHI)
      TBETA=DTAN(BETA)
      RK0=ONE-SPHI
      RKA=(ONE-SPHI)/(ONE+SPHI)
      RKP=ONE/RKA
      PU1=GAMMAD*Z*(DIA*(RKP-RKA)+Z*RKP*TPHI*TBETA)
      PU2=GAMMAD*DIA*Z*(RKP**3+TWO*RK0*RKP*RKP*
     +TPHI+TPHI-RKA)
      PUSAND=DMIN1(PU1,PU2)
      RETURN
      END
C----------------------------------------------------------
      FUNCTION SUMV(A,N,K)
C
C     THIS ROUTINE CALCULATES THE SUM OF ODD OR EVEN
C     NUMBERED
C     COMPONENTS OF A VECTOR 'A' OF SIZE N
C**********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     CALCULATIONS
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C**********************************************************
      DIMENSION A(N)
      DATA ZERO/0.0/
      SUMV=ZERO
      DO 10 I=1,N
      IF(MOD(I,2).EQ.K)SUMV=SUMV+A(I)
10    CONTINUE
      RETURN
      END
C----------------------------------------------------------
      FUNCTION ZNODE(NODE)
C
C     THIS ROUTINE CALCULATES THE DEPTH OF A PILE NODE
C     BELOW CAP
C**********************************************************
C     DEACTIVATE THE FOLLOWING LINE FOR SINGLE PRECISION
C     LINE
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C**********************************************************
      COMMON/PILE/TPL,E,RINER,AREA,DIA,X,ELENP,KCYC,
     +KSOIL,GSE,CL
      DATA ZERO/0.D0/
      X1=X
      IF(X1.EQ.ZERO)X1=TPL/16.D0
      ELENP=(TPL-X1)/15.D0
      IF(MOD(NODE,17).EQ.1)THEN
          ZNODE=ZERO
      ELSEIF(MOD(NODE,17).EQ.2)THEN
          ZNODE=X1
      ELSE
          ZNODE=X1+(MOD(NODE,17)-2)*ELENP
      ENDIF
      RETURN
```

```
      END
C-----------------------------------------------------------------
```

APPENDIX F
TYPICAL INPUT AND OUTPUT DATA SETS OF HOUSTON, TEXAS SINGLE AND NINE-PILE GROUP STUDY FOR PROGRAM LPG-VERSION 1 (PROFILE)

F.1 Input Data Set For Single Pile

```
TEXAS 3X3 GROUP,COMPRESSION,CYCLE#1
KIPS,INCH,RAD
1
480. 2.9e7 161. 11. 10.75
12. 0
1
50 1.e-4
2 842.3 .45
1.e-3

0.      0.      0.      0.      0.      0.
50.     70.     0.0355  0.      0.      0.
50.     70.     0.0355  0.      0.      0.
50.     70.     0.0355  0.      0.      0.
50.     70.     0.0355  0.      0.      0.
 0.     0.      0.      18.18305 .005   .01
 0.     0.      0.      18.71186 .005   .01
 0.     0.      0.      19.24067 .005   .01
 0.     0.      0.      19.76949 .005   .01
 0.     0.      0.      20.29830 .005   .01
 0.     0.      0.      20.82711 .005   .01
 0.     0.      0.      21.35593 .005   .01
 0.     0.      0.      21.88474 .005   .01
 0.     0.      0.      22.41355 .005   .01
 0.     0.      0.      22.94237 .005   .01
 0.     0.      0.      23.47118 .005   .01
 0.     0.      0.      24.00000 .005   .01


0.   0.

0 1 0 0 0

0  .20  0 0 0

1
```

F.2 Output Data Set For Single Pile

```
TEXAS 3X3 GROUP,COMPRESSION,CYCLE#1
*********************************************************************

                     ::::   L   P   G   ::::

   THIS PROGRAM CALCULATES THE LATERAL LOAD-DEFLECTION BEHAVIOR
   OF A PILE GROUP USING FEM TECHNIQUE.

*********************************************************************

                           I  N  P  U  T

   UNITS ARE                                     : KIPS,INCH,RAD


   CODE FOR PRINT OUT                        KFLG =          1

   TOTAL PILE LENGTH                            L =   480.         (L)
   YOUNG'S MODULUS OF PILE                      E =  0.290E+08     (F/L^2)
   MOMENT OF INERTIA OF PILE                    I =   161.         (L^4)
   AREA OF CROSS SECTION OF PILE                A =   11.0         (L^2)
   DIA OF PILE                                DIA =   10.8         (L)

   PROJECTION OF PILE GROUP ABOVE
          GROUND LEVEL                          X =   12.0         (L)
   # OF CYCLES OF LOAD APPLIED               KCYC =          0

   # OF PILES IN THE GROUP                  NPILE =          1
   MAXIMUM # OF ITERATIONS                 MAXITN =         50
   TOLERANCE                                TOLER =  0.100E-03     (L)

   SOIL TYPE                                KSOIL =          2
   SHEAR MODULUS OF SOIL                        G =   842.         (F/L^2)
   POISSONS RATIO OF SOIL                     RNU =  0.450

   PILE TIP STIFFNESS                       TSTIF =  0.100E-02     (F/L)

PY CURVES DATA:
                  PHI          K     GAMMA'         CU        E50       E100
                (DEG)   (F/L^3)   (F/L^3)    (F/L^2)      (L/L)      (L/L)

                    1          2          3          4          5          6
       1 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
       2 0.500E+02 0.700E+02 0.355E-01 0.000E+00 0.000E+00 0.000E+00
       3 0.500E+02 0.700E+02 0.355E-01 0.000E+00 0.000E+00 0.000E+00
       4 0.500E+02 0.700E+02 0.355E-01 0.000E+00 0.000E+00 0.000E+00
       5 0.500E+02 0.700E+02 0.355E-01 0.000E+00 0.000E+00 0.000E+00
       6 0.000E+00 0.000E+00 0.000E+00 0.182E+02 0.500E-02 0.100E-01
       7 0.000E+00 0.000E+00 0.000E+00 0.187E+02 0.500E-02 0.100E-01
       8 0.000E+00 0.000E+00 0.000E+00 0.192E+02 0.500E-02 0.100E-01
       9 0.000E+00 0.000E+00 0.000E+00 0.198E+02 0.500E-02 0.100E-01
      10 0.000E+00 0.000E+00 0.000E+00 0.203E+02 0.500E-02 0.100E-01
      11 0.000E+00 0.000E+00 0.000E+00 0.208E+02 0.500E-02 0.100E-01
      12 0.000E+00 0.000E+00 0.000E+00 0.214E+02 0.500E-02 0.100E-01
      13 0.000E+00 0.000E+00 0.000E+00 0.219E+02 0.500E-02 0.100E-01
      14 0.000E+00 0.000E+00 0.000E+00 0.224E+02 0.500E-02 0.100E-01
      15 0.000E+00 0.000E+00 0.000E+00 0.229E+02 0.500E-02 0.100E-01
      16 0.000E+00 0.000E+00 0.000E+00 0.235E+02 0.500E-02 0.100E-01
      17 0.000E+00 0.000E+00 0.000E+00 0.240E+02 0.500E-02 0.100E-01
```

```
PILE GEOMETRY:
    PILE#         X          Y
                  1          2
        1 0.000E+00 0.000E+00

BOUNDARY CONDITIONS CODE:
  FOR TRANSLATION IN Z DIRECTION =  0
                     X           =  1
                     Y           =  0
  FOR ROTATION ABOUT X AXIS      =  0
                     Y AXIS      =  0

CAP LOADS/DISPLACEMENTS:
    PILE#   FZZ/DZZ   FXX/DXX   FYY/DYY   MXX/RXX   MYY/RYY
                  1         2         3         4         5
        1 0.000E+00 0.200E+00 0.000E+00 0.000E+00 0.000E+00

# OF LOAD INCREMENT(S) =          1

*********************************************************************

TOTAL # OF MEMORY UNITS       =     550000
# OF MEMORY UNITS USED BY LPG =       8492
# OF MEMORY UNITS FREE        =     541508

*********************************************************************

                    ::::     OUTPUT    ::::

   GROUND SURFACE ELEVATION    =  0.120E+02 (L)

_____________________________________________________________________
_____________________________________________________________________
   THE SOLUTION CONVERGED FOR:
   DISPLACEMENT/FORCE INCREMENT #    =          1
                      ITERATION #    =          6
   MAX  DEFLECTION  ERROR            =  0.738E-04 (L)


_____________________________________________________________________
_____________________________________________________________________

APPLIED LOADS:
    PILE#       FZZ        FXX        FYY        MXX        MYY
                  1         2         3         4         5
        1 0.000E+00 0.447E+04 0.000E+00 0.000E+00 0.000E+00


 TOTAL =  0.000E+00 0.447E+04 0.000E+00 0.000E+00 0.000E+00

SUMMARY OF DISPLACEMENTS AT TOP OF PILE GROUP:
     PILE#          DZZ          DXX          DYY      THETAXX      THETAYY
                    (L)          (L)          (L)        (RAD)        (RAD)
                      1            2            3            4            5
         1  0.0000E+00  0.2000E+00  0.0000E+00  0.0000E+00 -0.3248E-02


 SUMMARY OF ABS MAXIMUM OUT-OF-BALANCE FORCES:
             FZZ =  0.000E+00  (F)
             FXX =  0.184E+03  (F)
             FYY =  0.000E+00  (F)
             MXX =  0.000E+00  (F-L)
```

MYY = 0.128E-08 (F-L)

CHECK: TOTAL LOAD CARRIED BY THE SOIL
(SUM OF NF+FF SOIL SPRINGS RESISTANCES)
IN X DIRECTION = 0.416E+04 (F)
IN Y DIRECTION = 0.000E+00 (F)

TOTAL LOAD APPLIED AT TOP OF PILE GROUP
IN X DIRECTION = 0.447E+04 (F)
IN Y DIRECTION = 0.000E+00 (F)

SUMMARY OF PILE ELEMENT FORCES:

1. MAX AXIAL FORCE (F)

PILE #	AXIAL FORCE
1	0.000

2. MAX SHEAR FORCE IN X DIRECTION (F)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	AT DEPTH BELOW CAP	MAX SF
1	1	0.000	12.000	0.4473E+04

3. MAX SHEAR FORCE IN Y DIRECTION (F)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	AT DEPTH BELOW CAP	MAX SF
1	1	0.000	12.000	0.0000E+00

4. MAX BENDING MOMENT ABOUT X AXIS (F-L)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	MAX BM
1	1	0.000	0.0000E+00

5. MAX BENDING MOMENT ABOUT Y AXIS (F-L)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	MAX BM
1	3	43.200	-0.1929E+06

****

F.3 Input Data Set For Nine-Pile Group

```
TEXAS 3X3 GROUP,COMPRESSION,CYCLE#1,LOAD#4-BANERJEE Gs
KIPS,INCH,RAD
1
480. 2.9e7 240.3116 90.7626 10.75
12. 0
9
50 1.e-4
2 842.3 .45
1.e-3

0.      0.      0.      0.       0.      0.
50.    70.      0.0355  0.       0.      0.
50.    70.      0.0355  0.       0.      0.
50.    70.      0.0355  0.       0.      0.
50.    70.      0.0355  0.       0.      0.
 0.     0.      0.      18.18305 .005   .01
 0.     0.      0.      18.71186 .005   .01
 0.     0.      0.      19.24067 .005   .01
 0.     0.      0.      19.76949 .005   .01
 0.     0.      0.      20.29830 .005   .01
 0.     0.      0.      20.82711 .005   .01
 0.     0.      0.      21.35593 .005   .01
 0.     0.      0.      21.88474 .005   .01
 0.     0.      0.      22.41355 .005   .01
 0.     0.      0.      22.94237 .005   .01
 0.     0.      0.      23.47118 .005   .01
 0.     0.      0.      24.00000 .005   .01


0.       64.5
32.25    64.5
64.5     64.5
0.       32.25
32.25    32.25
64.50    32.25
0.       0.
32.25    0.
64.50    0.

0 1 0 0 0

0  .87  0 0 0
0  .84  0 0 0
0  .81  0 0 0
0 1.06  0 0 0
0 1.01  0 0 0
0  .97  0 0 0
0 1.13  0 0 0
0 1.14  0 0 0
0 1.12  0 0 0

1
```

F.4 Output Data Set For Nine-Pile Group

```
TEXAS 3X3 GROUP,COMPRESSION,CYCLE#1,LOAD#4-BANERJEE Gs
*********************************************************************

                      ::::   L   P   G   ::::

   THIS PROGRAM CALCULATES THE LATERAL LOAD-DEFLECTION BEHAVIOR
   OF A PILE GROUP USING FEM TECHNIQUE.

*********************************************************************

                          I  N  P  U  T

   UNITS ARE                                   : KIPS,INCH,RAD


   CODE FOR PRINT OUT                    KFLG =          1

   TOTAL PILE LENGTH                        L =   480.         (L)
   YOUNG'S MODULUS OF PILE                  E =  0.290E+08     (F/L^2)
   MOMENT OF INERTIA OF PILE                I =   240.         (L^4)
   AREA OF CROSS SECTION OF PILE            A =   90.8         (L^2)
   DIA OF PILE                            DIA =   10.8         (L)

   PROJECTION OF PILE GROUP ABOVE
          GROUND LEVEL                      X =   12.0         (L)
   # OF CYCLES OF LOAD APPLIED           KCYC =          0

   # OF PILES IN THE GROUP              NPILE =          9
   MAXIMUM # OF ITERATIONS             MAXITN =         50
   TOLERANCE                            TOLER =  0.100E-03     (L)

   SOIL TYPE                            KSOIL =          2
   SHEAR MODULUS OF SOIL                    G =   842.         (F/L^2)
   POISSONS RATIO OF SOIL                 RNU =  0.450

   PILE TIP STIFFNESS                   TSTIF =  0.100E-02     (F/L)

PY CURVES DATA:
                PHI          K     GAMMA'         CU        E50       E100
              (DEG)    (F/L^3)    (F/L^3)    (F/L^2)      (L/L)      (L/L)

                  1          2          3          4          5          6
       1 0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
       2 0.500E+02  0.700E+02  0.355E-01  0.000E+00  0.000E+00  0.000E+00
       3 0.500E+02  0.700E+02  0.355E-01  0.000E+00  0.000E+00  0.000E+00
       4 0.500E+02  0.700E+02  0.355E-01  0.000E+00  0.000E+00  0.000E+00
       5 0.500E+02  0.700E+02  0.355E-01  0.000E+00  0.000E+00  0.000E+00
       6 0.000E+00  0.000E+00  0.000E+00  0.182E+02  0.500E-02  0.100E-01
       7 0.000E+00  0.000E+00  0.000E+00  0.187E+02  0.500E-02  0.100E-01
       8 0.000E+00  0.000E+00  0.000E+00  0.192E+02  0.500E-02  0.100E-01
       9 0.000E+00  0.000E+00  0.000E+00  0.198E+02  0.500E-02  0.100E-01
      10 0.000E+00  0.000E+00  0.000E+00  0.203E+02  0.500E-02  0.100E-01
      11 0.000E+00  0.000E+00  0.000E+00  0.208E+02  0.500E-02  0.100E-01
      12 0.000E+00  0.000E+00  0.000E+00  0.214E+02  0.500E-02  0.100E-01
      13 0.000E+00  0.000E+00  0.000E+00  0.219E+02  0.500E-02  0.100E-01
      14 0.000E+00  0.000E+00  0.000E+00  0.224E+02  0.500E-02  0.100E-01
      15 0.000E+00  0.000E+00  0.000E+00  0.229E+02  0.500E-02  0.100E-01
      16 0.000E+00  0.000E+00  0.000E+00  0.235E+02  0.500E-02  0.100E-01
      17 0.000E+00  0.000E+00  0.000E+00  0.240E+02  0.500E-02  0.100E-01
```

```
PILE GEOMETRY:
    PILE#          X          Y
                   1          2
        1 0.000E+00 0.645E+02
        2 0.323E+02 0.645E+02
        3 0.645E+02 0.645E+02
        4 0.000E+00 0.323E+02
        5 0.323E+02 0.323E+02
        6 0.645E+02 0.323E+02
        7 0.000E+00 0.000E+00
        8 0.323E+02 0.000E+00
        9 0.645E+02 0.000E+00

BOUNDARY CONDITIONS CODE:
  FOR TRANSLATION IN Z DIRECTION =  0
                     X           =  1
                     Y           =  0
  FOR ROTATION ABOUT X AXIS      =  0
                     Y AXIS      =  0

CAP LOADS/DISPLACEMENTS:
    PILE#    FZZ/DZZ   FXX/DXX   FYY/DYY   MXX/RXX   MYY/RYY
                   1         2         3         4         5
        1 0.000E+00 0.870E+00 0.000E+00 0.000E+00 0.000E+00
        2 0.000E+00 0.840E+00 0.000E+00 0.000E+00 0.000E+00
        3 0.000E+00 0.810E+00 0.000E+00 0.000E+00 0.000E+00
        4 0.000E+00 0.106E+01 0.000E+00 0.000E+00 0.000E+00
        5 0.000E+00 0.101E+01 0.000E+00 0.000E+00 0.000E+00
        6 0.000E+00 0.970E+00 0.000E+00 0.000E+00 0.000E+00
        7 0.000E+00 0.113E+01 0.000E+00 0.000E+00 0.000E+00
        8 0.000E+00 0.114E+01 0.000E+00 0.000E+00 0.000E+00
        9 0.000E+00 0.112E+01 0.000E+00 0.000E+00 0.000E+00

# OF LOAD INCREMENT(S) =          1

*********************************************************************

TOTAL # OF MEMORY UNITS         =     550000
# OF MEMORY UNITS USED BY LPG =     518900
# OF MEMORY UNITS FREE          =      31100

*********************************************************************


                    ::::     OUTPUT    ::::

   GROUND SURFACE ELEVATION    =  0.120E+02 (L)

---------------------------------------------------------------------
---------------------------------------------------------------------
   THE SOLUTION CONVERGED FOR:
   DISPLACEMENT/FORCE INCREMENT #    =          1
                     ITERATION #    =          5
   MAX  DEFLECTION  ERROR            =  0.479E-04 (L)


---------------------------------------------------------------------
---------------------------------------------------------------------

APPLIED LOADS:
    PILE#        FZZ        FXX        FYY        MXX        MYY
                   1          2          3          4          5
        1 0.000E+00 0.124E+05 0.291E-10-0.105E-08 0.000E+00
        2 0.000E+00 0.103E+05 0.100E-10-0.400E-10-0.931E-08
```

```
        3 0.000E+00 0.110E+05-0.946E-10 0.131E-08 0.186E-08
        4 0.000E+00 0.147E+05-0.728E-11-0.204E-09-0.540E-07
        5 0.000E+00 0.118E+05-0.105E-10 0.418E-10-0.279E-07
        6 0.000E+00 0.127E+05 0.109E-10-0.437E-10-0.205E-07
        7 0.000E+00 0.171E+05-0.728E-11 0.291E-10-0.186E-07
        8 0.000E+00 0.156E+05 0.728E-11 0.291E-10-0.168E-07
        9 0.000E+00 0.170E+05 0.218E-10-0.873E-10 0.317E-07

 TOTAL =    0.000E+00 0.123E+06-0.405E-10-0.127E-10-0.114E-06

SUMMARY OF DISPLACEMENTS AT TOP OF PILE GROUP:
     PILE#          DZZ          DXX          DYY      THETAXX      THETAYY
                    (L)          (L)          (L)        (RAD)        (RAD)
                      1            2            3            4            5
        1   0.0000E+00   0.8700E+00  -0.3257E-01  -0.2098E-03  -0.9441E-02
        2   0.0000E+00   0.8400E+00   0.2354E-02   0.1817E-04  -0.8615E-02
        3   0.0000E+00   0.8100E+00   0.3389E-01   0.2198E-03  -0.8559E-02
        4   0.0000E+00   0.1060E+01  -0.8517E-02  -0.6177E-04  -0.1159E-01
        5   0.0000E+00   0.1010E+01  -0.1395E-02  -0.1203E-04  -0.1035E-01
        6   0.0000E+00   0.9700E+00   0.7772E-02   0.5551E-04  -0.1028E-01
        7   0.0000E+00   0.1130E+01   0.2761E-01   0.1850E-03  -0.1292E-01
        8   0.0000E+00   0.1140E+01  -0.2667E-02  -0.1813E-04  -0.1258E-01
        9   0.0000E+00   0.1120E+01  -0.2929E-01  -0.1952E-03  -0.1279E-01


 SUMMARY OF ABS MAXIMUM OUT-OF-BALANCE FORCES:
                FZZ =   0.000E+00   (F)
                FXX =   0.420E+01   (F)
                FYY =   0.907E+01   (F)
                MXX =   0.134E-05   (F-L)
                MYY =   0.883E-06   (F-L)

CHECK: TOTAL LOAD CARRIED BY THE SOIL
      (SUM OF NF+FF SOIL SPRINGS RESISTANCES)
             IN X DIRECTION =   0.123E+06   (F)
             IN Y DIRECTION =  -0.418E-01   (F)

       TOTAL LOAD APPLIED AT TOP OF PILE GROUP
             IN X DIRECTION =   0.123E+06   (F)
             IN Y DIRECTION =  -0.405E-10   (F)

SUMMARY OF PILE ELEMENT FORCES:
___________________________

1.  MAX AXIAL FORCE (F)
____________________

       PILE         AXIAL
          #         FORCE

          1         0.000
          2         0.000
          3         0.000
          4         0.000
          5         0.000
          6         0.000
          7         0.000
          8         0.000
          9         0.000
```

2. MAX SHEAR FORCE IN X DIRECTION (F)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	AT DEPTH BELOW CAP	MAX SF
1	1	0.000	12.000	0.1241E+05
2	17	0.000	12.000	0.1033E+05
3	33	0.000	12.000	0.1105E+05
4	49	0.000	12.000	0.1467E+05
5	65	0.000	12.000	0.1176E+05
6	81	0.000	12.000	0.1270E+05
7	97	0.000	12.000	0.1715E+05
8	113	0.000	12.000	0.1563E+05
9	129	0.000	12.000	0.1700E+05

3. MAX SHEAR FORCE IN Y DIRECTION (F)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	AT DEPTH BELOW CAP	MAX SF
1	5	105.600	136.800	-0.2815E+03
2	26	261.600	292.800	0.2017E+03
3	37	105.600	136.800	0.3239E+03
4	53	105.600	136.800	-0.2574E+03
5	69	105.600	136.800	-0.6665E+02
6	85	105.600	136.800	0.2207E+03
7	101	105.600	136.800	0.3941E+03
8	122	261.600	292.800	-0.1550E+03
9	133	105.600	136.800	-0.3950E+03

4. MAX BENDING MOMENT ABOUT X AXIS (F-L)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	MAX BM
1	7	168.000	-0.1837E+05
2	26	261.600	-0.4552E+04
3	39	168.000	0.1889E+05
4	54	136.800	-0.8788E+04
5	70	136.800	-0.2435E+04
6	86	136.800	0.7361E+04
7	103	168.000	0.1814E+05
8	119	168.000	-0.3807E+04
9	135	168.000	-0.1833E+05

5. MAX BENDING MOMENT ABOUT Y AXIS (F-L)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	MAX BM
1	4	74.400	-0.5938E+06
2	20	74.400	-0.4915E+06
3	36	74.400	-0.5227E+06

4	52	74.400	-0.7256E+06
5	68	74.400	-0.5761E+06
6	84	74.400	-0.6181E+06
7	100	74.400	-0.8542E+06
8	116	74.400	-0.7790E+06
9	132	74.400	-0.8456E+06

****

APPENDIX G
TYPICAL INPUT AND OUTPUT DATA SETS FOR PROGRAM
LPG-VERSION 2 (LU)

G.1 Input Data Set For Single Pile

```
EXAMPLE PROBLEM TO ILLUSTRATE PILE SYMMETRY: SINGLE PILE, CLAY SOIL
LBS,INCHES,RADIANS
1
540. 1.0E7 2898.06 86.135 18.0
54. 0
1 1
50 1.E-4
2 600. 0.5
1.E6

0.      0.     0.        0.     .0       .0
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01
0.      0.     0.       18.     .005     .01

0.   54.

1

0 1 0 1 1

0 .3  0  0  0

1
```

G.2 Output Data Set For Single Pile

```
EXAMPLE PROBLEM TO ILLUSTRATE PILE SYMMETRY: SINGLE PILE, CLAY SOIL
*********************************************************************

                           ::::   L   P   G   ::::

   THIS PROGRAM CALCULATES THE LATERAL LOAD-DEFLECTION BEHAVIOR
   OF A PILE GROUP USING FEM TECHNIQUE.

*********************************************************************

                              I  N  P  U  T

   UNITS ARE                                    : LBS,INCHES,RADIANS


   CODE FOR PRINT OUT                      KFLG =           1

   TOTAL PILE LENGTH                          L =   540.        (L)
   YOUNG'S MODULUS OF PILE                    E =  0.100E+08    (F/L^2)
   MOMENT OF INERTIA OF PILE                  I =  0.290E+04    (L^4)
   AREA OF CROSS SECTION OF PILE              A =   86.1        (L^2)
   DIA OF PILE                              DIA =   18.0        (L)

   PROJECTION OF PILE GROUP ABOVE
          GROUND LEVEL                        X =   54.0        (L)
   # OF CYCLES OF LOAD APPLIED             KCYC =           0

   # OF PILES IN THE GROUP                NPILE =           1
   # OF ASYMMETRIC PILES IN THE GROUP       NPA =           1

   MAXIMUM # OF ITERATIONS               MAXITN =          50
   TOLERANCE                              TOLER =  0.100E-03    (L)

   SOIL TYPE                              KSOIL =           2
   SHEAR MODULUS OF SOIL                      G =   600.        (F/L^2)
   POISSONS RATIO OF SOIL                   RNU =  0.500

   PILE TIP STIFFNESS                     TSTIF =  0.100E+07    (F/L)

PY CURVES DATA:
                        PHI          K     GAMMA'         CU        E50       E100
                      (DEG)    (F/L^3)    (F/L^3)    (F/L^2)      (L/L)      (L/L)

                          1          2          3          4          5          6
              1 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
              2 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
              3 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
              4 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
              5 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
              6 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
              7 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
              8 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
              9 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
             10 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
             11 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
             12 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
             13 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
             14 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
             15 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
             16 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
             17 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
```

```
PILE GEOMETRY:
    PILE#         X         Y
                  1         2
        1 0.000E+00 0.540E+02


PILE SYMMETRY #(S):
   PILE #  SYMMETRY #
      1          1

BOUNDARY CONDITIONS CODE:
  FOR TRANSLATION IN Z DIRECTION =  0
                     X           =  1
                     Y           =  0
  FOR ROTATION ABOUT X AXIS      =  1
                     Y AXIS      =  1

CAP LOADS/DISPLACEMENTS:
    PILE#   FZZ/DZZ   FXX/DXX   FYY/DYY   MXX/RXX   MYY/RYY
                  1         2         3         4         5
        1 0.000E+00 0.300E+00 0.000E+00 0.000E+00 0.000E+00


   # OF CAP LOAD INCREMENT =           1
*********************************************************************

TOTAL # OF MEMORY UNITS          =    1550000
# OF MEMORY UNITS USED BY LPG =      20720
# OF MEMORY UNITS FREE           =    1529280

*********************************************************************


                    ::::     OUTPUT    ::::

   GROUND SURFACE ELEVATION    =  0.540E+02 (L)

_____________________________________________________________________
_____________________________________________________________________
   THE SOLUTION CONVERGED FOR:
   DISPLACEMENT/FORCE INCREMENT #     =           1
                      ITERATION #     =           8
   MAX  DEFLECTION  ERROR             =   0.895E-04 (L)


_____________________________________________________________________
_____________________________________________________________________

APPLIED LOADS:
    PILE#       FZZ       FXX       FYY       MXX       MYY
                  1         2         3         4         5
        1 0.000E+00 0.342E+05 0.000E+00 0.000E+00 0.231E+07


 TOTAL =  0.000E+00 0.342E+05 0.000E+00 0.000E+00 0.231E+07

SUMMARY OF DISPLACEMENTS AT TOP OF PILE GROUP:
     PILE#          DZZ          DXX          DYY      THETAXX      THETAYY
                    (L)          (L)          (L)        (RAD)        (RAD)
                      1            2            3            4            5
         1  0.0000E+00  0.3000E+00  0.0000E+00  0.0000E+00 -0.3234E-06
```

SUMMARY OF ABS MAXIMUM OUT-OF-BALANCE FORCES:

```
FZZ =  0.000E+00  (F)
FXX =  0.128E+03  (F)
FYY =  0.000E+00  (F)
MXX =  0.000E+00  (F-L)
MYY =  0.675E-08  (F-L)
```

CHECK: TOTAL LOAD CARRIED BY THE SOIL
(SUM OF NF+FF SOIL SPRINGS RESISTANCES)

```
IN X DIRECTION =  0.344E+05  (F)
IN Y DIRECTION =  0.000E+00  (F)
```

TOTAL LOAD APPLIED AT TOP OF PILE GROUP

```
IN X DIRECTION =  0.342E+05  (F)
IN Y DIRECTION =  0.000E+00  (F)
```

SUMMARY OF PILE ELEMENT FORCES:

1. MAX AXIAL FORCE (F)

PILE #	AXIAL FORCE
1	0

2. MAX SHEAR FORCE IN X DIRECTION (F)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	AT DEPTH BELOW CAP	MAX SF
1	1	0.000	54.000	0.3423E+05

3. MAX SHEAR FORCE IN Y DIRECTION (F)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	AT DEPTH BELOW CAP	MAX SF
1	1	0.000	54.000	0.0000E+00

4. MAX BENDING MOMENT ABOUT X AXIS (F-L)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	MAX BM
1	1	0.000	0.0000E+00

5. MAX BENDING MOMENT ABOUT Y AXIS (F-L)

PILE #	PILE ELEM#	AT DEPTH	MAX

		BELOW CAP	BM
1	1	0.000	0.2314E+07

****

G.3 Input Data Set For Four-Pile Pile Group

```
EXAMPLE PROBLEM TO ILLUSTRATE PILE SYMMETRY: 4X4 GROUP, CLAY SOIL
LBS,INCHES,RADIANS
1
540. 1.0E7 2898.06 86.135 18.0
54. 0
4 1
50 1.E-4
2 600. 0.5
1.E6

0.      0.     0.       0.    .0      .0
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01
0.      0.     0.      18.    .005    .01

0.   54.
54.  54.
0.    0.
54.   0.

1 1 1 1

0 1 0 1 1

0 .3  0  0  0

1
```

G.4 Output Data Set For Four-Pile Pile Group

```
EXAMPLE PROBLEM TO ILLUSTRATE PILE SYMMETRY: 4X4 GROUP, CLAY SOIL
**********************************************************************

                         ::::    L   P   G   ::::

   THIS PROGRAM CALCULATES THE LATERAL LOAD-DEFLECTION BEHAVIOR
   OF A PILE GROUP USING FEM TECHNIQUE.

**********************************************************************

                             I  N  P  U  T

   UNITS ARE                                    : LBS,INCHES,RADIANS


   CODE FOR PRINT OUT                     KFLG =          1

   TOTAL PILE LENGTH                         L =   540.         (L)
   YOUNG'S MODULUS OF PILE                   E =  0.100E+08     (F/L^2)
   MOMENT OF INERTIA OF PILE                 I =  0.290E+04     (L^4)
   AREA OF CROSS SECTION OF PILE             A =   86.1         (L^2)
   DIA OF PILE                             DIA =   18.0         (L)

   PROJECTION OF PILE GROUP ABOVE
          GROUND LEVEL                       X =   54.0         (L)
   # OF CYCLES OF LOAD APPLIED            KCYC =          0

   # OF PILES IN THE GROUP               NPILE =          4
   # OF ASYMMETRIC PILES IN THE GROUP      NPA =          1

   MAXIMUM # OF ITERATIONS              MAXITN =         50
   TOLERANCE                             TOLER =  0.100E-03     (L)

   SOIL TYPE                             KSOIL =          2
   SHEAR MODULUS OF SOIL                     G =   600.         (F/L^2)
   POISSONS RATIO OF SOIL                  RNU =  0.500

   PILE TIP STIFFNESS                    TSTIF =  0.100E+07     (F/L)

PY CURVES DATA:
                  PHI          K      GAMMA'         CU        E50       E100
                (DEG)    (F/L^3)    (F/L^3)    (F/L^2)      (L/L)      (L/L)

                    1          2          3          4          5          6
        1 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
        2 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
        3 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
        4 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
        5 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
        6 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
        7 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
        8 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
        9 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
       10 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
       11 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
       12 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
       13 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
       14 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
       15 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
       16 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
       17 0.000E+00 0.000E+00 0.000E+00 0.180E+02 0.500E-02 0.100E-01
```

```
PILE GEOMETRY:
    PILE#          X          Y
                   1          2
        1 0.000E+00 0.540E+02
        2 0.540E+02 0.540E+02
        3 0.000E+00 0.000E+00
        4 0.540E+02 0.000E+00


PILE SYMMETRY #(S):
   PILE #  SYMMETRY #
       1           1
       2           1
       3           1
       4           1

BOUNDARY CONDITIONS CODE:
  FOR TRANSLATION IN Z DIRECTION =  0
                     X           =  1
                     Y           =  0
  FOR ROTATION ABOUT X AXIS      =  1
                     Y AXIS      =  1

CAP LOADS/DISPLACEMENTS:
    PILE#   FZZ/DZZ   FXX/DXX   FYY/DYY   MXX/RXX   MYY/RYY
                  1         2         3         4         5
        1 0.000E+00 0.300E+00 0.000E+00 0.000E+00 0.000E+00


   # OF CAP LOAD INCREMENT =          1
**********************************************************************

TOTAL # OF MEMORY UNITS         =    1550000
# OF MEMORY UNITS USED BY LPG =      21040
# OF MEMORY UNITS FREE          =    1528960

**********************************************************************


                    ::::     OUTPUT    ::::

   GROUND SURFACE ELEVATION    =  0.540E+02 (L)

______________________________________________________________________
______________________________________________________________________
   THE SOLUTION CONVERGED FOR:
   DISPLACEMENT/FORCE INCREMENT #    =          1
                      ITERATION #    =          4
   MAX  DEFLECTION  ERROR            =  0.938E-05 (L)


______________________________________________________________________
______________________________________________________________________

APPLIED LOADS:
    PILE#         FZZ       FXX       FYY       MXX       MYY
                    1         2         3         4         5
        1 0.000E+00 0.165E+05 0.682E-12 0.114E+05 0.127E+07


 TOTAL =  0.000E+00 0.165E+05 0.682E-12 0.114E+05 0.127E+07

SUMMARY OF DISPLACEMENTS AT TOP OF PILE GROUP:
```

PILE#	DZZ (L) 1	DXX (L) 2	DYY (L) 3	THETAXX (RAD) 4	THETAYY (RAD) 5
1	0.0000E+00	0.3000E+00	-0.8946E-02	-0.1593E-08	-0.1771E-06

SUMMARY OF ABS MAXIMUM OUT-OF-BALANCE FORCES:

FZZ = 0.000E+00 (F)
FXX = 0.959E-01 (F)
FYY = 0.193E-01 (F)
MXX = 0.407E-09 (F-L)
MYY = 0.251E-07 (F-L)

CHECK: TOTAL LOAD CARRIED BY THE SOIL
(SUM OF NF+FF SOIL SPRINGS RESISTANCES)
IN X DIRECTION = 0.165E+05 (F)
IN Y DIRECTION = 0.143E-02 (F)

TOTAL LOAD APPLIED AT TOP OF PILE GROUP
IN X DIRECTION = 0.165E+05 (F)
IN Y DIRECTION = 0.682E-12 (F)

SUMMARY OF PILE ELEMENT FORCES:

1. MAX AXIAL FORCE (F)

PILE #	AXIAL FORCE
1	0

2. MAX SHEAR FORCE IN X DIRECTION (F)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	AT DEPTH BELOW CAP	MAX SF
1	1	0.000	54.000	0.1652E+05

3. MAX SHEAR FORCE IN Y DIRECTION (F)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	AT DEPTH BELOW CAP	MAX SF
1	5	151.200	183.600	-0.1886E+03

4. MAX BENDING MOMENT ABOUT X AXIS (F-L)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	MAX BM
1	2	54.000	0.1140E+05

5. MAX BENDING MOMENT ABOUT Y AXIS (F-L)

PILE #	PILE ELEM#	AT DEPTH BELOW CAP	MAX BM
1	1	0.000	0.1267E+07

****

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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